Modelling modified atmosphere packaging of Eksotika papaya
(Pemodelan pembungkusan atmosfera terubahsuai betik Eksotika)

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Key words: mathematical model, package design, steady-state concentration, permeability

Abstract
A mathematical model was developed to predict package size for fruit in modified atmosphere environments. The model was based on the packaging ratio required for providing a specific steady-state $O_2$ concentration. The model was verified using Eksotika papaya kept at low temperature. Results of the experiment showed the ability of the mathematical model to predict precise modified atmosphere package for papaya. The desired steady-state $O_2$ and $CO_2$ concentrations were achieved after about 3 days in storage and maintained close to the predicted levels until the end of the 3-week storage period. Ethylene concentration recorded in the package was low indicating that no ripening process occurred during storage.

Introduction
Fruit quality preservation by atmospheric manipulation, especially reduced oxygen ($O_2$) and increased carbon dioxide ($CO_2$) concentrations, has been widely used. Both low $O_2$ and high $CO_2$ concentrations reduce respiration rate, delay ripening and hence extend shelf life of the fruits. This principle has been adopted by many researchers for the development of modified atmosphere packaging (MAP) of fresh fruits including banana, papaya, rambutan, guava and starfruit (Kader et al. 1989; Abdullah et al. 1992). MAP in combination with low temperature storage may double the shelf life of fresh fruit as compared with the fruit without MAP. For maximum benefits of atmosphere storage, Powrie and Skura (1991) recommended an average combination of 2–5% $O_2$ and 5–10% $CO_2$ in MAP of highly respiring produce including banana, mango, papaya and pineapple.

Polymeric film has been used tremendously in MAP designs. Fruit packed...
with sealed polymeric film consumes O\textsubscript{2} and produces CO\textsubscript{2} from respiration activity. The outcome will be low O\textsubscript{2} and high CO\textsubscript{2} concentrations in the headspace of the package. The permeability of the film allows O\textsubscript{2} diffusion into the package and CO\textsubscript{2} diffusion out of the package. The mechanism creates an environment of acceptable low O\textsubscript{2} and high CO\textsubscript{2} concentrations for retention of fruit quality. Some of the common polymeric films used for fruit package include low density polyethylene (LDPE), high density polyethylene and polyvinyl chloride (Exama et al. 1993).

Many researchers developed MAP using mathematical models (Hayakawa et al. 1975; Henig and Gilbert 1975; Emond et al. 1991). Selection of suitable film and package dimensions for specific weight of fruit can be done using mathematical equations (Exama et al. 1993). The concentration of gases in the package can be predicted using computer programming with input parameters such as fruit respiration rate, film permeability and storage temperature. The performance of MAP to date, however, is inconsistent, especially for highly respiring produce such as tropical fruits.

This paper reports a study conducted to improve MAP designs of fresh fruits through modelling and computer simulation. Various factors influencing the performance of the package were analysed and considered in the model. The performance of the package developed was verified using Eksotika papaya.

Materials and methods
Model development
The main aim of any MAP design is to provide a suitable package for maintaining the concentration of gases needed to optimise a fruit storage system. Most of the available package models for respiring produce have been developed based on the Fick’s law of diffusion (Hayakawa et al. 1975; Henig and Gilbert 1975; Exama et al. 1993). The same law was also used to derive a package model at steady-state condition as follows:

\[ 0 = \frac{PA}{l} \left( \frac{C_a - C_{eq}}{100} \right) \pm WR \]  

where 

- \( P \) = film permeability (mm\textsuperscript{3}.mm/ mm\textsuperscript{2}.s.atm)
- \( A \) = film surface area (mm\textsuperscript{2})
- \( C_a \) = gas concentration outside the package (%)
- \( C_{eq} \) = steady-state gas concentration inside the package (%)
- \( l \) = film thickness (mm)
- \( W \) = fruit weight (kg)
- \( R \) = fruit respiration rate (mm\textsuperscript{3}/kg.s)
- \( \pm \) = O\textsubscript{2} (–) and CO\textsubscript{2} (+) respiratory gas

The equation is simplified further into:

\[ \frac{A}{W} = \frac{R_o l}{100 P_o (21 - C_{oeq})} \]  

\[ \frac{A}{W} = \frac{R_c l}{100 P_c C_{ceq}} \]

where 

- \( A/W \) = packaging ratio (mm\textsuperscript{2}/kg)
- \( o = O_2 \) gas
- \( c = CO_2 \) gas

Both equation 2 and equation 3 can be used for predicting the required size of polymeric film for MAP according to the desired O\textsubscript{2} and CO\textsubscript{2} concentrations. However, in most polymeric packages, O\textsubscript{2} is a limiting factor and will normally come to an equilibrium much earlier than CO\textsubscript{2} (Holland, R., CSIRO, New South Wales, Australia, Consultancy report on food packaging programme in Food Technology Research Centre, MARDI, not published 1992). Furthermore, the minimum tolerance of O\textsubscript{2} concentration for avoiding physiological injury in most fruits is estimated at 2\%, while the maximum limit
for CO$_2$ is at 10% (Kader et al. 1989). Therefore, it is essential to consider equation 2 for predicting package design based on the O$_2$ concentration, as CO$_2$ will come to equilibrium below 10%. Assuming that the respiratory quotient for fruit is about unity ($R_O = R_C$), the correlation between O$_2$ and CO$_2$ concentrations in the package can be derived from equation 2 and equation 3, and simplified as follows:

$$C_{ceq} = \frac{(21 - C_{oeq})}{P_R}$$  \hspace{1cm} (4)

where $P_R$ = permeability ratio or $P_c / P_o$

**Package design**

A computer program was developed to assist in the prediction of the optimum package size for fruit. The flowchart diagram of the program is shown in Figure 1. The program was fed with parameters such as fruit type, rate of respiration ($R$), type of packaging material, film permeability ($P$), film thickness ($l$), weight of fruit per package ($W$) and steady-state O$_2$ concentration ($C_o$) desired for the fruit. In this study, the package for individual fruit of Eksotika papaya was designed using LDPE film. Respiration rate of Eksotika papaya measured at MARDI (Rohani, M. Y., MARDI, Serdang, data not published 1992) and permeability of LDPE film reviewed by Pauly (1989) were used as input parameters for the design (Table 1). All parameters were converted accordingly to reflect the temperature and surrounding atmosphere of the experiment. As recommended for most tropical fruits (Kader et al. 1989), the O$_2$ concentration of about 5% was selected as the desired steady-state concentration of Eksotika papaya in the package. However, the predicted steady-state O$_2$ and CO$_2$ concentrations in the package were calculated based on actual area of film and weight of fruit used in the verification.

![Figure 1. Computer flowchart diagram for predicting the optimum package size of papaya](image-url)
Table 1. Design parameters fed into the computer program

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Data</th>
<th>Condition</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Respiration rate of Eksotika papaya (mm$^3$/kg.s)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Oxygen or carbon dioxide</td>
<td>2.83</td>
<td>Air, at 10 °C</td>
<td>MARDI</td>
</tr>
<tr>
<td></td>
<td>2.00</td>
<td>MA, at 15 °C</td>
<td>Conversion</td>
</tr>
<tr>
<td>Permeability of LDPE film (mm$^3$.mm/mm$^2$.s.atm)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Oxygen</td>
<td>1.21 x 10$^{-6}$</td>
<td>15 °C</td>
<td>Pauly (1989)</td>
</tr>
<tr>
<td>Carbon dioxide</td>
<td>5.53 x 10$^{-6}$</td>
<td>15 °C</td>
<td>Pauly (1989)</td>
</tr>
</tbody>
</table>

Table 2. Predicted packaging ratio for package designs of Eksotika papaya using LDPE film

<table>
<thead>
<tr>
<th>Film thickness (mm)</th>
<th>O$_2$ (%)</th>
<th>CO$_2$ (%)</th>
<th>Packaging ratio (mm$^2$/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.03</td>
<td>2</td>
<td>4.17</td>
<td>2.60 x 10$^5$</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>3.51</td>
<td>3.09 x 10$^5$</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>2.85</td>
<td>3.81 x 10$^5$</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>2.41</td>
<td>4.50 x 10$^5$</td>
</tr>
<tr>
<td>0.04</td>
<td>2</td>
<td>4.17</td>
<td>3.47 x 10$^5$</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>3.51</td>
<td>4.12 x 10$^5$</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>2.85</td>
<td>5.07 x 10$^5$</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>2.41</td>
<td>6.00 x 10$^5$</td>
</tr>
<tr>
<td>0.05</td>
<td>2</td>
<td>4.17</td>
<td>4.34 x 10$^5$</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>3.51</td>
<td>5.15 x 10$^5$</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>2.85</td>
<td>6.34 x 10$^5$</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>2.41</td>
<td>7.49 x 10$^5$</td>
</tr>
</tbody>
</table>

**Model verification**

Performance of the package was verified using Eksotika papaya fruit obtained from a commercial farm at Bidor, Perak. Fruit at maturity stage 2 (skin colour green with traces of yellow) were selected, washed and allowed to dry at ambient. The fruit were weighed individually and values were used for computation of film area needed in the package design. Three thicknesses of LDPE film (0.03, 0.04 and 0.05 mm) were selected as package design treatments for verification. Based on the predicted output (Table 2), packaging ratios (A/W) of about 3 x 10$^5$, 4 x 10$^5$ and 5 x 10$^5$ mm$^2$/kg were used for 0.03, 0.04 and 0.05 mm thickness of films respectively. The area of film required was computed by multiplying the selected packaging ratio with the exact weight of fruit. In the experiment, fruit were packed individually and sealed properly to avoid any leaking. Each package design treatment was replicated six times. The fruit were kept in cold storage at 15 °C for 3 weeks.

**Measurement of gas**

The concentrations of O$_2$, CO$_2$ and ethylene in all packages were measured twice a week. The O$_2$ and CO$_2$ were measured using a Varian 1420 gas chromatograph (GC) equipped with a thermal conductivity detector, while ethylene concentration was measured using a Varian 1400 GC equipped with a flame ionization detector. For each measurement, 1 mL of the headspace gas was withdrawn from each package using an air-tight hypodermic syringe and injected into a particular stainless steel GC column. The data were statistically analysed with analysis of variance and regression analysis for comparison with predicted output.

**Results and discussion**

Packaging ratios on LDPE film of varying thicknesses were predicted for package designs of Eksotika papaya. As shown in Table 2, packaging ratio varies according to the thickness of film and desired steady-state O$_2$. The thicker the packaging film, the larger the packaging ratio needed to achieve the specific MA environment in the package. For LDPE film, output result in Table 2 can be used as guidelines for developing appropriate size of package per weight of fruit. The computation is accurate provided that the value of permeability used in the prediction is not influenced by...
variation in thickness of film and the polymeric material used in the manufacturing of the film (Pauly 1989). However, in actual situation, different permeability values may be recorded for different thickness of film and produced by different manufacturer due to the differences in drawing, orientation and crystallinity. Furthermore, small fluctuation of the storage temperature may also influence the permeability of the film. Although the temperature of the cold room used in the experiment was recorded at about 15 ± 2 °C, the effect of temperature fluctuation was not considered in the prediction.

Result from the verification trials showed that the O₂ concentration in all packages declined and moved towards equilibrium after about 3 days in storage, although it was slightly delayed in 0.03 mm package (Figure 2). Similar trends were also observed for CO₂ concentration, where the steady-state condition was achieved after about 3 days of storage. The pattern of the result was in agreement with previous studies on broccoli and strawberry (Emond et al. 1991), tomato (Gong and Corey 1994) and bell pepper (Fishman et al. 1995). The observed steady-state O₂ and CO₂ in all packages were 4.9–5.6% and 3.4–4.1% respectively, which were significantly close ($p < 0.05$) to the respective predicted concentrations of about 4.5% and 3.6% (Table 3). The steady-state condition was maintained until the end of the 3-week experimental period.

The correlation between CO₂ concentration and O₂ concentration in MA package can be calculated using equation 4 and compared with observed correlation for all three films (0.03, 0.04 and 0.05 mm). As shown in Figure 3, the regression analysis of observed result performed a linear correlation of $C_o = 21 - 4.29C_C$ (with $R^2 = 0.74$) and agreed closely ($p < 0.05$) with predicted correlation of $C_o = 21 - 4.57C_C$. The slope of the equation is known as the permeability ratio ($P_R$) for the LDPE film. The observed permeability ratio was about

Figure 2. Oxygen and carbon dioxide concentrations inside papaya packages using three thicknesses of LDPE films and stored at 15 °C (mean of 6 replicates)
Table 3. Mean steady-state O₂ and CO₂ composition in papaya packages

<table>
<thead>
<tr>
<th>Film thickness (mm)</th>
<th>O₂ (%)</th>
<th>CO₂ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.03</td>
<td>5.59a</td>
<td>3.42a</td>
</tr>
<tr>
<td>0.04</td>
<td>5.46ab</td>
<td>3.48ab</td>
</tr>
<tr>
<td>0.05</td>
<td>4.91bc</td>
<td>4.05b</td>
</tr>
<tr>
<td>Predicted</td>
<td>4.51c</td>
<td>3.62ab</td>
</tr>
</tbody>
</table>

Mean values in the same column with the same letters are not significantly different at $p < 0.05$ according to DMRT.

4.29, which was close to the predicted value of 4.57. The result of the correlation suggested that for any level of O₂, the CO₂ concentration accumulated in the MAP was less than 5%. This is one of the advantages in using LDPE film for packing fruits. It allows modification of CO₂ atmosphere below 10%, that is the maximum tolerance limit to avoid physiological disorder in most tropical fruits (Kader et al. 1989).

Ethylene concentration in the package was measured to evaluate any possible ripening process in the package. The result showed that the overall ethylene concentration in all packages was quite low (less than 1.5%), confirming that ripening process did not occur during storage (Figure 4). However, the concentration in 0.05 mm package began to rise after 15 days of storage indicating that the ripening process was about to commence (Ali et al. 1994). This is obvious since the storage temperature (15 °C) and atmospheric composition (4.9–5.6% O₂ and 3.4–4.1% CO₂) of the experiment were not the optimum condition for the storage of Eksotika papaya. Research results (Abd. Shukor, A. R., MARDI, Serdang, data not published 1995) suggested using atmospheric composition of 2% O₂ and 5% CO₂ at 12 °C for the storage of Eksotika papaya up to 32 days. The use of 15 °C in the present study was only to verify the precision of the mathematical model for designing MA package.

Conclusion
The verification of the model showed that the mathematical equation was able to predict the area of film required for developing MAP. The use of packaging ratio as design output was very practical since it provided a constant packaging ratio for a particular thickness of film. The appropriate packaging ratio of film was selected according to the desired steady-state MA concentration in the package. Gong and Corey (1994) also used packaging ratio when they designed and evaluated MAP for...
tomato. The actual area of film used in the package can easily be calculated by multiplying the packaging ratio with the exact weight of fruit for each pack. The study also considered the permeability ratio of film as another important parameter influencing the overall steady-state $O_2$ and $CO_2$ composition in the package. Film with permeability ratio of about 4.5 was able to develop MA system and ensure $CO_2$ concentration of less than 10% limit for most tropical fruits.

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References

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