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Modeling Respiration Rate of Bell Pepper (*Capsicum anuum* L.) Under Hypobaric Storage Through Dimensional Analysis

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ABSTRACT

Knowing the respiration rate of fresh products during storage is very important. One can use direct measurement or available prediction equations to determine the respiration rate. However, the availability of the prediction equations still needs to be improved. This study aims to develop mathematical models of respiration rate for pretreated bell peppers during hypobaric storage. Model development was done by applying dimensional analysis. Mature green bell peppers were used as the experimental samples. Three pretreatments on the bell pepper before storage, namely control, ozone pretreatment, and UV-C pretreatment, combined with three hypobaric storage levels of 26, 64, and 101 kPa, were studied. An apparatus set was built to create hypobaric conditions. An ozone generator and UV-C lamp were used to apply pretreatments to the samples. It was found that respiration rate models could be developed by considering bell pepper surface area, weight, volume, storage time, storage volume, and pressure. At the storage pressures of 101 to 56 kPa, UV-C pretreatment was the best in suppressing the respiration rate of bell pepper. Meanwhile, at a storage pressure of 26 kPa, the application of ozone and UV-C pretreatment gave a higher respiration rate than the control. The three models were found to have different characteristics and showed high accuracy with the experimental results. The dimensionless product of π3 was found to have the most significant effect on RCO_2 for the three models. This finding indicated that the ratio between bell pepper and jar volumes is critical to ensure the model works.

Keywords: Bell pepper, hypobaric storage, ozone, respiration, UV-C

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INTRODUCTION

Bell pepper (*Capsicum annuum* L.) plays an essential role in many different cuisines worldwide with its various flavors and colors (Frans et al., 2021). Green bell pepper is a vital source of antioxidants, vitamins, and dietary fiber (Howard et al., 2000; Bosland et al., 2012; Rubatzky & Yamaguchi, 2012; Chen et al., 2018). However, bell pepper is a perishable product with a relatively short shelf life. Therefore, some treatments should be applied to extend its shelf life.

Ozonation is one of the promising chemical treatments to inactivate microorganisms and degrade mycotoxins (Gomes et al., 2020; Trombete et al., 2017). Ozone is an unstable molecule that rapidly decays to diatomic oxygen without leaving food residues and has the GRAS (Generally Recognized As Safe) status (Gaou et al., 2005; Gutiérrez et al., 2018). This treatment is faster than other conventional disinfection methods and without harmful residues. Many studies of ozone application on fresh products have been carried out, such as the application of ozone on cantaloupe (Chen et al., 2020), apples (Lv et al., 2019), oranges (García-Martín et al., 2018), and carrots (de Souza et al., 2018). It was also reported that ozone pretreatment on cantaloupe reduces respiration rate, ethylene production, and the number of microorganisms and maintains a high hardness level (Chen et al., 2020). Ong et al. (2014) find that papayas treated with ozone at concentrations lower than 5 ppm have a lower respiration rate and delayed ripening compared to controls. Considering these findings, it is reasonable to apply ozone pretreatment on the bell pepper in this study.

Ultraviolet-C (UV-C) irradiation is another new potential and environmentally friendly technology to extend the shelf life of fruits and vegetables (Lwin et al., 2021). It has been applied in many research works to prolong the self-life and maintain the quality of fresh products. UV-C treatment reduces respiration rate and maintains the quality of fresh products (Zhang & Jiang, 2019; Rodoni et al., 2015). Lwin et al. (2021) reported that irradiation of UV-C with a dose of 4.4 kJ/m^2 maintains baby corn's texture and total sugar concentration. The effect of UV-C irradiation in reducing respiration rate has also been reported for many products in various research works. Vicente et al. (2005) found that UV-C irradiation at 7 kJ/m^2 reduced the respiration rate of red chili Rodoni et al. (2015) for fresh-cut peppers, and Ustun et al. (2021) for green beans. Therefore, UV-C radiation is feasible for reducing bell pepper's respiration rate in this study.

Storing fresh produce in an environment with low oxygen concentrations can also extend the product's shelf life. Low oxygen concertation can slow the respiration rate of fresh produce, remove ethylene and other metabolic volatiles, retard the progress of ripening and aging (Burg, 2014). Reducing oxygen concentration in the storage space can be done by lowering the chamber's air pressure, known as hypobaric. It is a cheap and easy way to reduce oxygen concentration in storage space. Wang and Dilley (2000) stated that better and easier preservation of fresh produce under hypobaric conditions is thought to be due to modification of the low-oxygen atmosphere and removal of volatile metabolic products such as ethylene and α-pharmacies from the atmosphere of storage facilities. The effect of hypobaric treatment in suppressing respiration rate was also reported for strawberry fruit (An et al., 2009), tomato fruit (Kou et al., 2016) and asparagus (Li et al., 2006). Hashmi et al. (2014) point out that combining hypobaric and other treatments, such as UV-C, heat ultrasound or volatile chemicals, may improve the storability of strawberries.

Respiration can be defined as a metabolic process that provides energy for the biochemical processes of fresh products. The respiration rate must be known because it is essential to control ripening to ensure quality after harvest and monitor product quality during storage. The respiration rate is inversely related to the product's shelf life, and efforts for shelf-life enhancement focus mainly on decreasing respiration (Waghmare et al., 2013). Respiration rate, usually expressed as the rate of O_2 consumption or CO_2 evolution, helps predict the shelf life of the products. Measurement of the respiration rate is sometimes very difficult to do. In hypobaric storage, measuring the respiration rate is problematic since O2 dan CO2 measuring devices are commonly designed for atmospheric pressure. Therefore, it is necessary to build models that can be used to predict respiration rates in the hypobaric storage condition. There are still many other situations where theoretically developed models are essential for postharvest agricultural product handling. Because it is often that in many postharvest activities, the relationship among parameters is not known clearly, causing analytical solutions not to be applied. In such a situation, dimensional analysis can solve the problem.

Dimensional analysis is one of the methods that can be used to develop a mathematical model of any phenomenon, mainly for cases where the relationship among the variables that influence the phenomenon cannot be related analytically. Pexton (2014) stated that dimensional analysis helps explain a phenomenon found in a process and is described as a mathematical model. In addition, the dimensional analysis makes it possible to state which phenomena have a significant influence and which play a minor role (Kowalczyk & Delgado, 2007). Several researchers have utilized dimensional analysis in the postharvest handling of agricultural products to develop predictive equations for certain phenomena. Moradi et al. (2016) applied dimensional analysis to develop equations to predict the moisture content of aloe vera gel. Jimoh et al. (2016) formulated prediction models for cassava peeling performance.

Nwakuba et al. (2017) developed an equation to predict the drying rate of the cocoa beans. Saracoglu (2018) used dimensional analysis to construct a plum drag force model, Asonye et al. (2018) developed equations for the cutting energy of okra, and Moradi et al. (2019) developed models for the physical and mechanical properties of three cultivars of cucumber fruit. Because the relationship between respiration rate variables during hypobaric storage is unclear, dimensional analysis can be used to form a prediction equation for the respiration rate. Considering the above descriptions, this study aimed to develop mathematical models of the respiration rate of bell peppers pretreated using ozone and UV-C during hypobaric storage by applying dimensional analysis.

MATERIALS AND METHODS

Respiration Rate Model Development Using Dimensional Analysis

The respiration rate in the form of CO_2 production (RCO_2) during storage of bell peppers in the hypobaric condition is affected by several parameters. There were unlimited parameters that might affect a particular phenomenon. However, considering too many parameters will make the resulting mathematical equation too long, impractical and complex (Sonin, 2001). In this study, the formulation of the respiration rate was intended for bell peppers stored under hypobaric conditions at room air temperature. They were pretreated using ozone and UV-C; no treatment was performed before storage. For that reason, the parameters, along with their dimensions and units considered to affect the respiration rate, were summarized in Table 1.

Table 1
Considered parameters in the development of the respiration rate model of bell pepper stored under hypobaric condition

No	Parameter	Symbol	Unit	Dimension
Dependent parameter				
1.	Respiration rate	RCO_2	$m^3\,kg^{-1}\,day^{-1}$	$L^3\,M^{-1}\,T^{-1}$
Independent parameter				
2.	Bell pepper surface area	A	m^2	L^2
3.	Bell pepper mass	w	kg	M
4.	Bell pepper volume	Vb	m^3	L^3
5.	Storage time	t	day	T
6.	Jar volume	Vr	m^3	L^3
7.	Jar absolute pressure	P	N/m^2	$ML^{-1}\,T^{-2}$

According to the Buckingham π theorem, these parameters could be related to Equation (1).

$$\pi = A^{k1}, w^{k2}, Vb^{k3}, t^{k4}, Vr^{k5}, P^{k} \quad [1]$$

The number of dimensionless products (π) formed was equal to the number of parameters involved minus the number of dimensions (Sonin, 2001; Thurairajasingam et al., 2002; Gibbings, 2011; Olmos et al., 2015; Loubière et al., 2019). Therefore, there were 7 parameters and 3 dimensions for the case studied here, so 4 dimensionless products will be obtained. Through some standard calculations of the Buckingham π theorem, the four dimensionless products are shown in Equations 2 to 5.

$$\pi 1 = \frac{R_{CO\,2}.w^{1.5}}{Vb.Vr^{0.17}.P^{0.5}} \quad [2]$$

$$\pi 2 = \frac{A^{1.5}}{Vr} \quad [3]$$

$$\pi 3 = \frac{Vb}{Vr} \quad [4]$$

$$\pi 4 = \frac{t.Vr^{0.17}.P^{0.5}}{w^{0.5}} \quad [5]$$

These four dimensionless products could be related as a functional Equation 6.

$$\pi 1 = C\,(\pi 2)^{a}\,(\pi 3)^{b}\,(\pi 4)^{c} \quad [6]$$

Substituting Equations 2 to 5 into Equation 6 resulted in Equation 7. The constant values of *C*, *a*, *b*, and *c* of Equation 7 could be determined by applying multiple linear regression analysis to the experimental data. Then, a mathematical model for predicting the respiration rate could be expressed as Equation 8.

$$\frac{R_{CO\,2}.w^{1.5}}{Vb.Vr^{0.17}.P^{0.5}} = C\left[\frac{A^{1.5}}{Vr}\right]^{a}\left[\frac{Vb}{Vr}\right]^{b}\left[\frac{t.Vr^{0.17}P^{0.5}}{w^{0.5}}\right]^{c} \quad [7]$$

$$R_{CO2} = C\left[\frac{Vb.Vr^{0.17}.P^{0.5}}{w^{1.5}}\right]\left[\frac{A^{1.5}}{Vr}\right]^{a}\left[\frac{Vb}{Vr}\right]^{b}\left[\frac{t.Vr^{0.17}.P^{0.5}}{w^{0.5}}\right]^{c} \quad [8]$$

Materials

Green bell peppers of spider variety in a green mature state were used as the samples in this research. These bell peppers were bought directly from the farmer in Batu, East Java, Indonesia. The bell peppers were transported to the laboratory inside a closed box at night. On arrival at the laboratory, the peppers were cleaned using a wet cloth to remove adhering dirt, sorted and selected, where only fresh, free of defect, and homogenous in color were used in the research. The selected bell pepper's weight, volume, and surface area must be measured individually before being stored in the respirometer jar.

Apparatus

The arrangement of the hypobaric apparatus used in this research is presented in Figure 1. This apparatus consisted of a vacuum pump (Value VE180N, 3/4 HP), a holding tank (30 × 15 cm), a vacuum controller unit, a glass jar (123 × 150 mm), and other supported components such as valve, hose, and clamps. The arrangement of these components would create a vacuum condition in the glass jar or respirometer container automatically as desired. The vacuum pump functioned to create a vacuum pressure in the respirometer

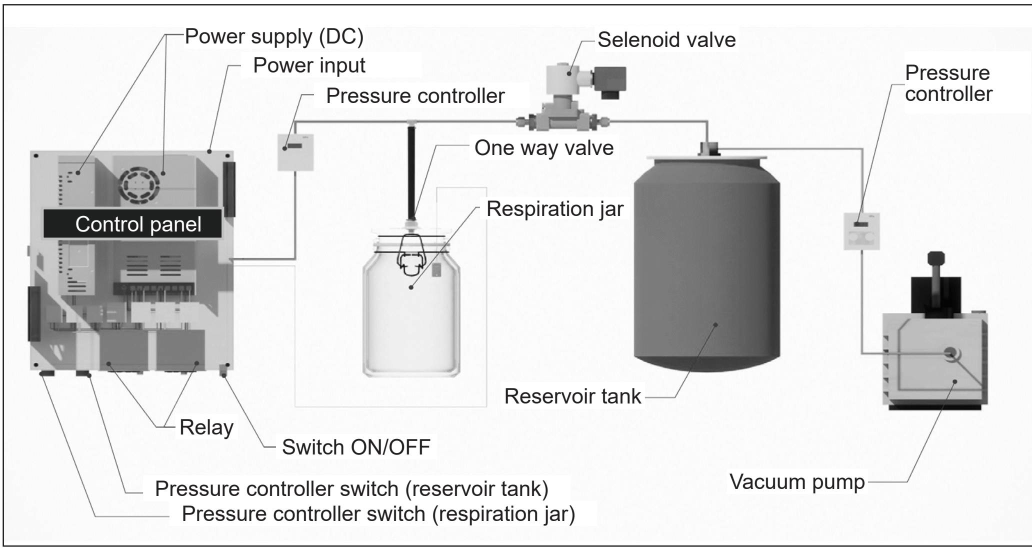


Figure 1. The arrangement of the hypobaric apparatus used in the experiment

jars. A holding or reservoir tank was used to stabilize the pressure in the system. The vacuum controller unit was used to regulate the desired pressure by opening and closing the solenoid valve and turning on and off the pump. Glass jar with a volume of 2118 ml was used as the respirometer container to store the bell pepper sample and was equipped with a pneumatic hose, one-way valve, and a vacuum pressure meter (SMC ZSE40-T1-22L and Panasonic DP-100). A total of 27 glass jars were used in this study to accommodate all treatment combinations.

In this research, the bell pepper sample was pretreated by exposing it to ozone gas or UV-C light before being stored in the respirometer glass jar. This pretreatment was carried out to better reduce the respiration rate and maintain the quality of the bell pepper sample. A UV-C fluorescent lamp (Sankyo Denki G40T10 and Philips TUV 36W/G36 T8) was used to apply the irradiation process to the bell pepper sample. The process was done in a specially designed exposure cabinet made from wood with 149.5 × 45.3 × 110 cm dimensions. The magnitude of irradiation intensity was monitored using a UV-C light meter (Lutron, 254SD) with a white ball-shaped UVC-light probe constructed in a special housing with a measurement range of 2 mW/cm^2. In this study, the intensity of UV-C radiation used was 0.834 mW/cm^2 for 6 minutes or 3 kJ/m^2. This intensity was chosen based on the values commonly used in the various research works, where this value was in the range of the suggested intensities. Fonseca and Rushing (2008) suggested that the optimal UV-C dose for maximum hormesis effect ranged from 0.125 to 9 kJ/m^2 to control the growth of plant pathogens. Hassan et al. (2020) used UV-C intensities of 3.5, 7.0, and 10.4 kJ/m^2 for hot pepper, fennel and coriander; Ma et al. (2021) used 0.25 kJ/m^2 for paprika; and Yan et al. (2021) used 4 kJ/m^2 for tomato.

An ozone generator machine (PX-902) was used to apply another pretreatment to the bell pepper sample. The sample was put in a plastic container (47 × 32 × 24 cm) with inlet and outlet holes. Ozone gas from the generator then flowed through a plastic hose into the container until the concentration of ozone gas in the plastic container reached 4.99 ppm, which took about 4 minutes. This concentration was left until it reached 0 ppm, which took about 8 minutes. The concentration of ozone gas in the container was monitored using an ozone gas detector (Dienmern, Dm-509-O3). The concentration of ozone gas used in this study was selected based on various research reports on the application of ozone gas in various studies. Srilaong et al. (2013) used ozone concentrations of 2 and 10 ppm for mango fruit, Ali et al. (2014) used 0–5 ppm for papaya fruit, Han et al. (2017) applied ozone gas concentration of 2 ppm for mulberry fruit, García-Martín et al. (2018) used 1.6–60 ppm for orange fruit, Lv et al. (2019) used 2.5 ppm for apple, Lin et al. (2019) used 1.99 ppm for red suren, and Chen et al. (2020) applied 3, 5, and 7 ppm for melon fruit. The selected ozone gas concentration used in this study was in the range or about the average concentration value used by the above researchers.

Methods

Selected bell pepper was measured for dimension, weight, and volume and then pretreated by exposing it to the predetermined ozone gas or UV-C. Unpretreated bell pepper was also used as a control treatment. Therefore, this study carried three different pretreatments: gas ozone pretreatment, UV-C pretreatment, and no pretreatment (control). After being pretreated, a bell pepper was stored in the respirometer glass jar, and the cover was tightly closed. Each respirometer jar was filled with one of the bell pepper samples. The jar was vacuumed to the predetermined absolute pressure values by adjusting the vacuum controller unit. This research observed three different vacuum or hypobaric conditions of 26 kPa, 64 kPa and 101 kPa (atmospheric pressure). The hypobaric conditions of 26 kPa, 64 kPa and 101 kPa correspond with O_2 concentrations in the jar of 5%, 13% and 21%, respectively. A gas analyzer (Quantek 902D) was used to monitor the concentration of CO_2 in the jar. CO_2 gas measurements in vacuum conditions (under normal atmospheric pressure) are carried out by inserting the needle of the CO_2 measuring device (Quantek 902D) into the glass jar of the respirometer where the bell pepper is placed. Due to the pressure conditions in the vacuum respirometer jar, CO_2 gas from the respirometer jar will automatically flow into the CO_2 measuring device, and the CO_2 sensor in the measuring device will detect the CO_2 concentration value. In this measurement process, the suction pump from the CO_2 measuring device does not need to be turned on. In this way, CO_2 gas measurements can be carried out smoothly. The absolute pressure was monitored using a vacuum pressure meter (SMC ZSE40- T1-22L and Panasonic DP-100). The jar was then stored at tropical room temperature of about 25–28°C for 15 days. The change in CO_2 concentration in the jar was measured daily for 15 days of storage. Three replications were carried out for each treatment combination.

Parameter Measurement

The weight of the bell pepper sample was measured using a digital balance (Model MH-200, range of 0–200 g/0.01 g). The volume was measured using the water displacement method. The surface area of the bell pepper was found by calculating the measured fruit and stalk dimensions of the sample using a digital caliper. The surface area was obtained by the sum of the fruit (*Af*) and the stalk (*As*) surface area using Equations 9 and 10, respectively. In this calculation, the bell pepper was assumed to be a frustum for the fruit portion and a cylinder for the stalk. Figure 2 shows the measured dimensions of the fruit and stalk used in this research.

$$Af = \pi.(R+r)\{h^2+(R-r)^2\}^{\frac{1}{2}} + \pi r^2 + \pi R^2 - \frac{1}{4}.\pi.\left(\frac{d1+d2+d3}{3}\right)^2 \quad [9]$$

$$As = \pi.\left(\frac{d1+d2+d3}{3}\right).l + \frac{1}{4}.\pi.(d_l)^2 \quad [10]$$

The bell pepper sample's weight, volume, and surface area were assumed to be constant throughout the storage period. The same was true for the volume and absolute pressure in the respirometer jar. The concentration of CO_2 in the jar was monitored daily during storage. The bell pepper's respiration rate was calculated using Equation 11 (Kays, 1991; Fonseca et al., 2002).

$$R_{CO2} = \frac{Vf\ (CO_{2t} - CO_{2i})}{W\ (t - ti)\ 100} \quad [11]$$

Where RCO_2 was the respiration rate of the bell pepper (ml/kg.h); *Vf* was the free volume inside the jar (ml); CO_{2i} and CO_{2t} were CO_2 concentrations at the initial and at time *t* (%), respectively; *W* was the weight of the bell pepper sample (kg), and *t* and *ti* were certain of storage time and initial storage time (hour).

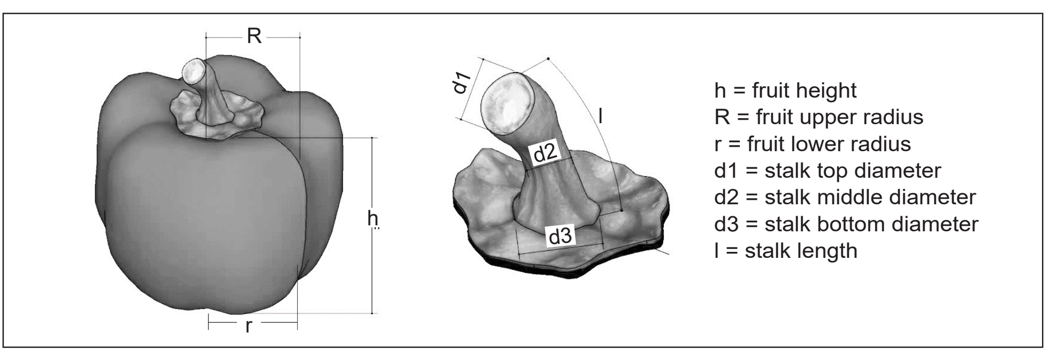


Figure 2. Schematic presentation of the dimensions of fruit and stalk of bell pepper

From the measurement of the involved parameters during the experiment, the values of $\pi 1$ to $\pi 4$ could be calculated, as shown in Table 2. The range of these values will also be the limits of the applicability of the developed equations.

Table 2
The range of π values calculated from measured parameters in the research

Pretreatment	π1	π2	π3	π4
Ozone	1.461×10^{-9} - 8.443×10^{-9}	1.296-2.406	0.094-0.161	0.114×10^{8} - 3.746×10^{8}
UV-C	1.069×10^{-9} - 5.529×10^{-9}	0.748-2.060	0.094-0.151	0.099×10^{8} - 4.117×10^{8}
Control	0.106×10^{-9} - 10.20×10^{-9}	1.471-2.372	0.104-0.179	0.107×10^{8} - 3.361×10^{8}

RESULTS AND DISCUSSION

Model of Bell Pepper Respiration Rate

Based on the values of $\pi 1$ to $\pi 5$ obtained in this research, constant values of Equation 8 could be found using multiple regression analysis. Therefore, models or equations for the respiration rate of the three pretreatment conditions could be determined in Equations 12 to 14.

$$RCO_{2\ Ozone} = 4.692x10^{-5} \left[\frac{Vb.Vr^{0.17}.P^{0.5}}{w^{1.5}}\right]\left[\frac{A^{1.5}}{Vr}\right]^{0.688}\left[\frac{Vb}{Vr}\right]^{1.555}\left[\frac{t.Vr^{0.17}.P^{0.5}}{w^{0.5}}\right]^{-0.360} \quad [12]$$

$$RCO_{2\ UV-C} = 1.52x10^{-5} \left[\frac{Vb.Vr^{0.17}.P^{0.5}}{w^{1.5}}\right]\left[\frac{A^{1.5}}{Vr}\right]^{-0.622}\left[\frac{Vb}{Vr}\right]^{0.811}\left[\frac{t\ Vr^{0.17}\,P^{0.5}}{w^{0.5}}\right]^{-0.359} \quad [13]$$

$$RCO_{2\ Control} = 1.310x10^{-2} \left[\frac{Vb.Vr^{0.17}.P^{0.5}}{w^{1.5}}\right]\left[\frac{A^{1.5}}{Vr}\right]^{-2.446}\left[\frac{Vb}{Vr}\right]^{4.403}\left[\frac{t.Vr^{0.17}\,P^{0.5}}{w^{0.5}}\right]^{-0.274} \quad [14]$$

The constant values of the model for ozone, UV-C, and control were found to be different. The respiration rates of bell peppers in the three conditions differed. In other words, ozone or UV-C pretreatment would change the respiration rate of bell peppers. The enforceability of the respiration rate models resulting from this study had limits according to the range of $\pi 1$ to $\pi 4$ values, as shown in Table 2.

Figure 3 presents RCO_2 values according to the developed models for the storage pressures from 26 to 101 kPa in 15 kPa intervals. It could be observed that the respiration rate of the three treatments decreased with the storage time. At the beginning of the storage time until about five days, respiration rates decreased faster than the rest of the storage days, suggesting that the greatest decrease in the respiration rate occurred at the beginning of the storage period, indicating that changes in the qualities of the bell pepper were likely to occur during this period. Collings et al. (2018) also found that the respiration rate of Fresh P. nigrum berries decreased faster at the beginning of the storage period. It was also reported that the rate of change of CO_2 and O_2 was faster in the early hours of mango packaging (Devanesan et al., 2012).

Ozone pretreatment showed the highest respiration rate at a storage pressure of 101 kPa to 71 kPa (Figures 3a to 3c**)** and was almost the same as the control but much higher than the UV-C pretreatment. It indicated that ozone pretreatment had no inhibitory effect on the respiration rate at those storage pressures. The effect of ozone in reducing respiration rate was getting better at 56 kPa storage pressure. However, further decreasing storage pressure to 41 kPa or lower (Figures 3e and 3f) decreases effectiveness, even giving a higher respiration rate than the control. The optimal ozone pretreatment storage pressure was about 56 kPa (Figure 3d). This result was very close to those reported by An et al. (2009) and Muhammad et al. (2023), who reported that a hypobaric pressure of 50 kPa was the best for strawberries and tomatoes, respectively. However, ozone pretreatment's effectiveness was less than UV-C for all studied storage pressures.

Templalexis et al. (2023) reported that the respiration rate of ozone-pretreated fresh-cut lettuce increased compared to the control. Arya et al. (2016) also found that the respiration rate of oyster mushrooms pretreated with 10 and 20 ppm ozone gas was larger than the control. Khawarizmi et al. (2018) stated that ozone was naturally decomposed into oxygen, which could contribute to a higher respiration rate of oxygen-sensitive commodities. On the contrary, Lin et al. (2023) found that the ozone-treated fresh-cut water fennel respiration rate was lower than that of the control. Cao et al. (2022) also found a lower ozone-pretreated kiwi fruit respiration rate than the control. The difference in research findings about the relationship between ozone treatment and respiration rate proves that more research is still needed to reveal ozone's true role in a product's respiration rate. As further stated by Khawarizmi et al. (2018), several parameters, such as ozone concentration, exposure time, and product sensitivity to ozone, were important factors that must be considered in research.

It was also observed that UV-C pretreated bell pepper showed the lowest respiration rate at storage pressure from 101 to 56 kPa (Figures 3a to 3d). However, further lowering the storage pressure to 41 kPa or lower, the respiration rate of UV-C pretreatment increased and was higher than that of the control (Figures 3e and 3f). It indicated that the effectiveness of UV-C pretreatment in suppressing respiration rate decreased as storage pressure decreased. It was the same phenomenon as ozone pretreatment, as mentioned above. According to this result, if UV-C pretreatment should be combined with the hypobaric storage, the lowest storage pressure could be applied at around 56 kPa. Therefore, it was suggested that reducing the respiration rate at a storage pressure of 101 to 56 kPa would be more effective if the bell pepper was treated with UV-C instead of using ozone.

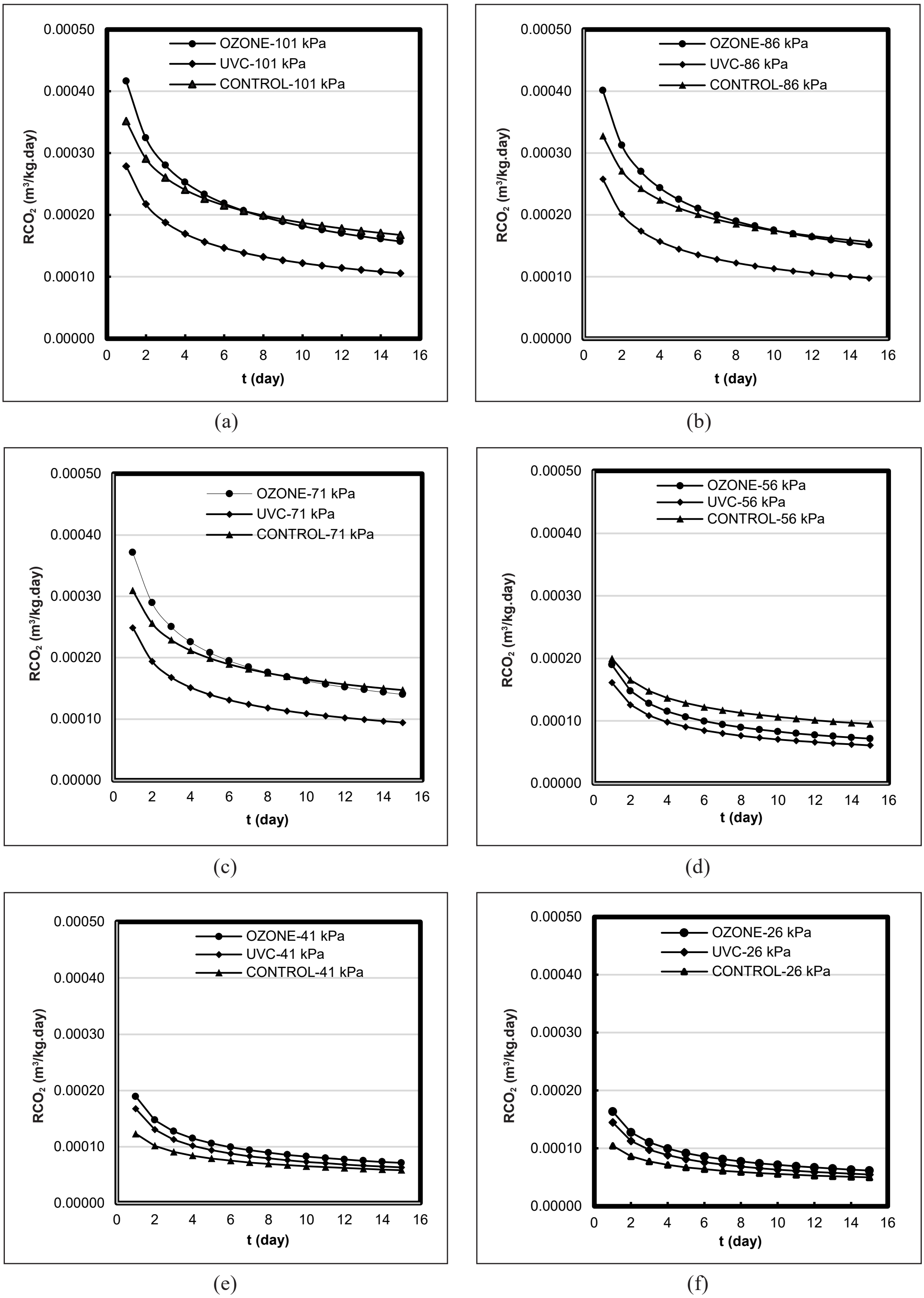


Figure 3. RCO_2 of the bell pepper during hypobaric storage, according to the developed models: (a) 101 kPa; (b) 86 kPa; (c) 71 kPa; (d) 56 kPa; (e) 41 kPa; and (f) 26 kPa storage pressures

Figure 3f showed that the effectiveness of UV-C pretreatments in reducing respiration rate was getting less at a storage pressure of 26 kPa compared to the control. The same was valid for ozone pretreatment, which meant that the effect of UV-C and ozone pretreatments on the respiration rate of bell pepper storage under hypobaric conditions depended on the storage pressure. At the storage pressure of 26 kPa, the control had the lowest respiration rate, meaning that ozone or UV-C pretreatment was not necessary at this storage pressure. In other words, for the storage pressure of 26 kPa and the temperature of 28^{o}C, applying ozone or UV-C to the bell pepper would negatively affect the respiration rate. UV-C irradiation activates several biological processes and increases respiratory rate (Yemmireddy et al., 2022). Squash slices also experienced increased respiration rates with UV treatment ((Erkan et al., 2001) and shallots at a storage temperature of 28°C and RH 76.1% (Fauziah et al., 2020). The storage temperature used would also influence the effect of UV-C treatment on the respiration rate.

Kim et al. (2012) found that UV-LED irradiation decreased the respiration rate of cherry tomatoes at a storage temperature of 10°C while there was no obvious effect at 20^{o}C. According to Allende et al. (2006), UV-C light has the potential to activate several biological processes in higher plants, including stimulation of respiration activity. Vunnam et al. (2014) reported that UV-C-treated cherry tomatoes had the highest respiration rate compared to the control treatment and fruit stored in modified atmospheres packaging (MAP). From these results, there are still many discrepancies regarding the effect of UV-C pretreatment on respiration rate. Its effectiveness depended on the irradiation dose, duration of the exposure time, storage temperature, and storage room pressure, and it was even found to not affect the respiration rate. Therefore, more comprehensive research was still needed to reveal the role of UV-C irradiation on the respiration rate of fresh produce. Similar statements were pointed out by other researchers in various research works, such as Gimeno et al. (2022) in a study about the application of UV-C in MAP.

Hashmi et al. (2014) in the study of hypobaric application for strawberry fruit. Furthermore, it is stated that the application of hypobaric in conjunction with other physical treatments such as UV-C, heat and ultrasound and volatile chemical treatments still needs to be evaluated. It was also observed that the respiration rate of the three pretreatment conditions consistently decreased with decreasing storage pressure. This finding indicated that storage pressure could effectively reduce the respiration rate of the bell pepper samples. Chen et al. (2013) reported similar results for bayberry fruit. Kou et al. (2016) also found that the respiration rates of tomatoes significantly decreased in the hypobaric condition. At the same time, Li et al. (2019) reported that hypobaric treatment only had little effect on the respiratory rate of blueberry fruit. The lower respiration rate in hypobaric conditions was due to the lower availability of oxygen in the space of the container, which caused the respiration rate to decrease.

As aforementioned, at 101 kPa, the concentration of oxygen in the container was the same as free air or about 21%, while at 64 kPa, the concentration of oxygen was reduced to 15%, and further reduction the storage pressure to 26 kPa, the concentration of oxygen was only 5%. This study showed that the combination of ozone or UV-C pretreatment and storage pressure was best at around 56 kPa, or about half of the atmospheric pressure. Some researchers also pointed out similar results for different treatment combinations. Muhammad et al. (2023) recommended that the best combination between the application of 400 ppm $KMnO_4$ with the storage pressure was found for the storage pressure of 50 kPa for tomato fruit. An et al. (2009) reported that a storage pressure of 50.7 kPa gave a slightly better ascorbic acid content and a lower growth of bacteria compared to the control for strawberry fruit.

Templalexis et al. (2023) found that the effectiveness of UV-C pretreatment in reducing the respiration rate of fresh-cut lettuce depended on the duration of the exposure time; as the exposure time increased, the effectiveness decreased. Mabusela et al. (2023) found that direct exposure to Vacuum Ultraviolet radiation on Fuji apple successfully reduced the respiration rate but damaged the skin, and UV-C pretreatment produced a lower respiration rate during the shelf life of Yellow Peaches (Zhou et al., 2020). Cote et al. (2013) reported that UV-C irradiation did not affect the respiration rate of tomatoes. Similar results were found by Collings et al. (2018) that UV-C treatment practically had no certain effect on the respiration rate of fresh piper nigrum berries compared to the control.

Model Validation

Comparisons between observed and predicted respiration rates using the developed model, as shown in Equations 13 to 15, are presented in Figure 4. The predicted respiration rate values were relatively close to the experimental results, meaning that the three developed models could be used to estimate the respiration rate in practice. As mentioned, it was still very rare and difficult to measure the respiration rate in the hypobaric condition; therefore, these equations would be very valuable in estimating the respiration rate of bell pepper in the hypobaric condition. An et al. (2009) pointed out that very few studies had directly reported respiration data as a function of the hypobaric partial pressure of the component gases. Thus, more measurement data were needed to quantitatively describe respiration as a function of hypobaric condition variables.

One of the advantages of using this model was that it was not necessary to measure O_2 and CO_2 concentrations directly on a respirometer, which was known to be quite difficult in hypobaric conditions because O_2 and CO_2 measuring instruments were generally designed for non-hypobaric conditions or atmospheric air pressure. The accuracy of the developed models to predict the respiration rate was evaluated using the determination coefficient (R^2) Equation 15, root mean square error (RMSE) Equation 16, percentage error (PE) Equation

17, mean absolute percentage error (MAPE) Equation 18, chi-square ($\chi 2$) Equation 19 and the results are presented in Table 3.

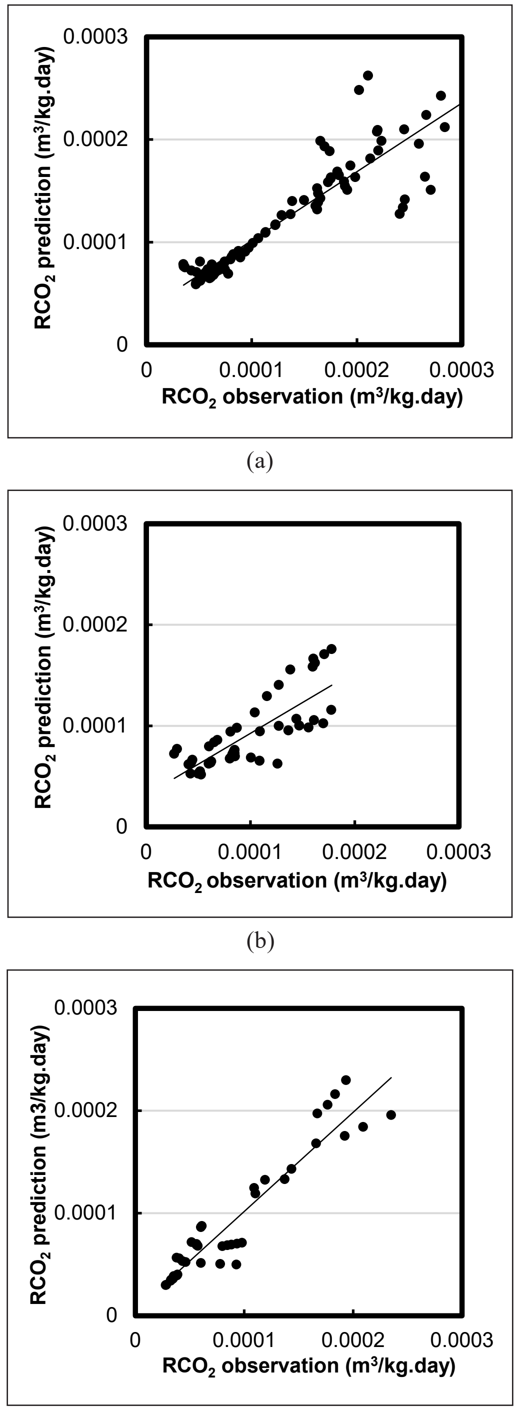
$$R^2 = \frac{\sum(MR_{exp} * MR_{pre})^2}{\sum(MR^2{}_{exp} * MR^2{}_{pre})} \quad [15]$$

$$RMSE = \left[\frac{1}{N}\sum_{i=1}^{n}(X_{i,exp} - X_{i,pre})^2\right]^{1/2} \quad [16]$$

$$MAPE = \frac{\sum_{t=1}^{n}\left|\left(\frac{A_t - F_t}{A_t}\right)100\right|}{n} \quad [17]$$

$$\chi^2 = \frac{\sum_{i=1}^{N}(X_{i,exp} - X_{i,pre})^2}{N - Z} \quad [18]$$

It could be seen that the R^2 values were relatively high, along with small values of RMSE, PE, MAPE, and χ^2. The greater the R^2 value, the closer to 1, the higher the effect (Susmiati, 2022). MAPE has important, desirable features, including reliability, ease of interpretation, presentation clarity, and statistical evaluation support (Moreno et al., 2013). Meanwhile, a model has a very accurate forecast if the MAPE value is below 10% and a good forecast if the MAPE value is between 10% and 20% (Lewis, 1982). The smaller the RMSE and MAPE values, the smaller the deviation between the predicted and observed values so that the model used is more accurate. Models that provide smaller RMSE and MAPE values are more accurate and in accordance with actual conditions (Shintawati et al., 2020). The smaller the Chi-square value (χ^2), the more precise the prediction equation, but in general, there are no limitations. Table 3 indicated that the developed models of the respiration rate were accurate and might be used to predict the respiration rate of



(b)

Figure 4. Comparison between observed and predicted respiration rates: (a) ozone pretreatment, (b) UV-C pretreatment; and (c) control

Table 3
Parameters to evaluate the accuracy of the models

Pretreatment	*R2*	*RMSE*	*PE* (%)	*MAPE*	χ^2
Ozon	0.956	3.476×10^{-5}	0.199	19.468	0.0008
UV-C	0.933	3.639×10^{-5}	0.447	25.009	0.0007
Control	0.879	6.579×10^{-5}	0.374	20.959	0.0012

bell peppers in the hypobaric storage condition. It also suggested that the formulation of models for respiration rate could be carried out by applying dimensional analysis. Table 3 indicated that the developed models of the respiration rate were accurate and might be used to predict the respiration rate of bell peppers in the hypobaric storage condition. It also suggested that formulation of the model for respiration rate could be carried out by applying dimensional analysis.

Sensitivity Analysis

The effect of changing the values of the dimensionless products of $\pi 2$ to $\pi 4$ on RCO_2 can be seen from the sensitivity analysis in Table 4. It was found that within 10% increasing or decreasing the values of $\pi 2$, $\pi 3$, and $\pi 4$, the dimensionless product of $\pi 3$ had the largest effect on RCO_2 for the three models. This finding indicated that the ratio between bell pepper volume to jar volume ($\pi 3$) was the most significant parameter affecting RCO_2. It was also observed that for ozone-pretreated bell pepper, as the values of $\pi 2$ and $\pi 3$ increased, the values of RCO_2 would increase too; however, increasing the values of $\pi 4$ would decrease RCO_2. Meanwhile, UV-C pretreatment and control were found to have the same tendency. Increasing the values of π2 and $\pi 4$ would decrease RCO_2 while increasing $\pi 3$ would increase RCO_2. These findings would be beneficial for estimating the respiration rate of bell peppers when designing a hypobaric storage system.

Table 4
Sensitivity analysis effect of π2, π3, and π4 on RCO_2

Pretreatment	Dimensionless product	Change in RCO_2 value (%)		Average change in RCO_2 value (%)
		10% increase	10% decrease	
Ozone	$\pi 2$	24.325	21.389	22.857
	$\pi 3$	30.081	23.166	26.623
	$\pi 4$	21.595	23.060	22.327
UV-C	$\pi 2$	25.667	30.908	28.288
	$\pi 3$	31.641	25.413	28.527
	$\pi 4$	26.277	29.392	27.834
Control	$\pi 2$	22.601	48.765	35.683
	$\pi 3$	69.055	33.418	51.236
	$\pi 4$	25.572	29.135	27.353

CONCLUSION

The respiration rate models of bell peppers could be formulated during hypobaric storage by applying dimensional analysis. The parameters used to develop the models consisted of bell pepper surface area, bell pepper weight, bell pepper volume, storage time, storage volume, and storage pressure. Three respiration rate models were developed for control, ozone pretreated and UV-C pretreated bell peppers, and they were found to have different characteristics. At the storage pressures of 101 to 56 kPa, UV-C pretreatment was the best in suppressing the respiration rate of bell pepper. Meanwhile, at a storage pressure of 26 kPa, the application of ozone and UV-C pretreatment gave a higher respiration rate than the control. It was also observed that the developed respiration rate models had quite high accuracy, in which dimensionless products of $\pi 3$, the ratio of bell pepper volume to jar volume parameter, had the largest effect on RCO_2 for the three models.

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