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MEASUREMENT AND MODELLING OF RESPIRATION RATE AND ENERGY BALANCE OF BANANAS AND ITS ECONOMIC IMPACT DURING THE STORAGE

Tarek FOUDA[1], Adel Hamed EL-BAHNASAWY[2], Nourhan KASSAB[1]

[1]Tanta University, Faculty of Agriculture, Agriculture Engineering Department, Egypt, E-mails: tfouda628@gmail.com, nour_kassab2308@gmail.com
[2]Benha University, Faculty of Agriculture, Agriculture Engineering Department, Egypt,
E-mail: adel.bahnasawy@fagr.bu.edu.eg

Corresponding author: tfouda628@gmail.com

Abstract

The aim of this study the effect of respiration rate and ventilation rate in the fruit ripening models and estimate the oxygen consumption and CO_2 production. In this investigation, with three banana ripening models .Model 1's have 72 m³ space had thermally insulated cement walls that were 30 mm thick; Model 2's 60 m³ area was similarly insulated with cement walls, but these walls were 12.5 mm thick; and Model 3's 38 m³ area was insulated with ceramic walls, 24 mm thick. The measurement indicators were the oxygen consumption, CO_2 production, Ventilation Rate, Temperature-Dependent Respiration Rate, heat production during respiration and energy balance. The findings demonstrated that the three ripening models' data were considerably impacted by temperature, model size, and banana ripening stages, where ripe bananas in model 1 (the largest) recorded the highest values in respiration rate, ventilation requirements and respiration temperature of bananas, where the values reached 187.556 g CO_2/kg/h, 2.55 m_3/h and 82.57 kW, respectively. The economic impact of banana storage reflects an increase in the profit period and thus a shortened investment Payback period.

Key words: *banana, ripening, respiration and ventilation rate, energy balance, economic efficiency*

INTRODUCTION

The word "banana" (*Musa paradisiaca* L.) refers to a variety of species or hybrids of the Musaceae family's genus Musa. Grown in almost 120 countries, bananas are a staple item that is essential to the economic and nutritional health of millions of people in the poor globe [12].
In 2023, 139 million tons bananas were produced at the global level. Bananas are mostly produced in Asia, Africa, South America and Central America. The largest producer of bananas is India.
The main exporting countries are Ecuador, Philippines, Costa Rica and Guatemala [20].
The United Nations Food and Agriculture Organization reports that banana exports were constant in 2023, increasing by 0.29% year over year to 19.17 million metric tons. Another FAO report stated that 19.1 million metric tons of bananas were exported in 2022 [9].
Improper handling and ripening techniques could lead to bananas losses.
The losses could emerge during various stages along the fruit supply chain.
First, it could be mentioned harvesting and pre-harvesting, then transportation, storage, processing, packing, and marketing.
Various authors researched studied the causes which determine losses of bananas weight and quality and proposed strategies to reduce them throughout the chain of supply [17, 16, 19, 2, 12, 4].
Table 1 lists the reasons why bananas are lost during the supply chain. Table 1 lists the supply chain's phases.
Harvested plant products' living cells constantly breathe, taking in oxygen (O_2) from the surroundings and exhaling carbon dioxide (CO_2).

Table 1. The stages along the supply chain when bananas could achieve losses

Supply chain stages	Causes of banana losses
(i)Harvesting and pre-harvesting	Spoilage and trimming
(ii)Transport	Bruising, breakage and infection as a result of dust, heat, rain and humidity
(iii)Storage	Over or under ripening.
(iv)Processing and packing	Incorrect processing and inefficient packing
(v) Marketing	Multi-level handling, weight loss, quality loss.

Source: Adapted by author based on [17].

Numerous compounds present in the cells undergo oxidation-reduction processes during respiration, converting them to CO_2. It is one of the main causes of perishables' postharvest losses both quantitatively and financially, with a deep impact of the famers' and ripeners' income. Fresh produce's postharvest respiratory response is influenced by the temperature of the storage air as well as its O_2, CO_2, and ethylene content [3].

In general, low temperature, low O_2, and slightly higher CO_2 reduce enzyme activity, which slows the pace at which substrates (such carbohydrates, organic acid, and other reserves) are used and prolongs the fruit's postharvest life beyond its normal range.

Therefore, two important external parameters that may be controlled to retain the fruit in perfect condition as long as possible after its typical season are the storage temperature and the composition of the storage air [18].

Bananas are picked green and then delivered to the market areas, where they are allowed to mature. Fruits often split and get mealy when allowed to ripen on the tree. For importers and ripeners, the pre-climacteric period after harvesting is critical because bananas are shipped before they ripen. Mature green fruits produce nearly no ethylene during this time, and their basal respiration rate is modest. The "green life" (GL) is another name for this time frame, and the longest feasible "pre-climacteric period" is desired. The duration of this period depends on several factors, including as temperature, relative humidity (RH), and the amount of ethylene present in the ambient air. As the fruit ripens, respiration and autocatalytic ethylene production rise quickly in climacteric fruits, such as bananas. In actuality, the GL period ends at this critical point when the ripening process is initiated by a number of enzymes involved in the ethylene synthesis pathway [10].

In order to provide the energy needed by the product to advance its metabolic processes, a number of substrates are oxidized during the respiration process. Approximately 2,880 kJ, or the energy needed to fully oxidize one mole of hexose, is released during aerobic respiration. The rate of respiration is closely related to the amount of oxygen in the surrounding atmosphere since respiration is dependent on the presence of oxygen. Reduced oxygen partial pressure delays ripening, which also lowers respiration rate and the quantity of chemical energy released that can be used to carry out the product's metabolic processes [14].

The temperature and composition of the storage air, specifically the amounts of O_2, CO_2, and ethylene, affect the post-harvest respiratory response of fresh food. Reduced enzymatic activity caused by low temperature, low O_2, and slightly elevated CO_2 usually results in a slower rate of substrate consumption (carbohydrates, organic acid, and other reserves), extending the fruit's post-harvest life beyond its regular lifetime. Thus, the storage temperature and the air composition in the storage are two crucial external factors that may be managed to maintain the fruit in optimal condition for as long as feasible after its typical season [19].

Fruits and vegetables release CO_2, break down carbohydrates into their more basic forms, and absorb O_2 from the atmosphere. The rate of biochemical and physiological processes is determined by the fresh product's respiration rate, which is influenced by the temperature and various gas concentrations in the storage location. The respiration rate is often linked to the deterioration of fresh fruits and vegetables. The exchange of oxygen and carbon dioxide gases is the main process of respiration, and the experiment is conducted in an airtight chamber. The variation in O_2 and CO_2 gas concentrations within the closed chamber explains the fresh product's respiration rates.

The product's freshness can be preserved by increasing the CO_2 content and decreasing the oxygen content [11].

The most obvious ripening-related change in banana fruit is the color shift from green to yellow. Softening, variations in sugar and acidity, and the emergence of volatile scents are further aspects of fruit ripening that increase the fruit's commercial appeal. To increase the fruit's nutritional content and reduce postharvest losses, it is crucial to comprehend the mechanisms underlying fruit ripening. The phytohormone ethylene affects a variety of aspects of plant growth and development, including senescence, organ abscission, and fruit ripening. Fruit ripening is categorized as either climacteric or non-climacteric based on whether a peak in ethylene release and an increase in respiration is linked to the process. By controlling the expression of genes involved in several biological processes, ethylene controls the ripening of fruit, such as enhanced respiration, autocatalytic ethylene synthesis, color accumulation, texture alterations, and the development of overall fruit quality attributes [8].

Takes time and specialized gas analysis equipment to measure the gas composition and produce respiration rate at a certain storage temperature. To connect the respiration rate to various storage parameters, such as temperature and gas composition (e.g., O2 and CO2), numerous mathematical models have been devised. Enzyme kinetics is the basis of the more current method for estimating respiration rate using the Michaelis-Menten type equation. Assuming that the transport and solubility of O_2 and CO_2 in plant tissue govern allosteric enzyme-catalyzed reactions, this provides a fundamental explanation of respiration [5].

Fresh fruits are usually in high demand on the market. Fruits, however, have a short shelf life and are perishable items. Fruit degeneration starts as soon as the fruit is separated from the parent plant and is associated with physiological and biochemical processes. Cells in living plant products breathe continuously, absorbing oxygen (O_2) from their environment and releasing carbon dioxide (CO_2). During respiration, a sequence of oxidation-reduction reactions converts several molecules within the cells to CO_2 [7].

Transpiration and respiration are the two physiological processes that most frequently take place when bananas ripen. The green banana exhibits a momentary decrease in transpiration rate. The ripening stage of bananas is when the transpiration rate peaks. The physical and chemical alterations that take place during the ripening and storage phases of banana fruit have a major influence on the fruit's skin color. As the banana fruit ripens and is preserved, it changes from green to yellow [1].

Technology for atmospheric preservation is essential for controlling respiration and microbial development when storing fruits and vegetables. Respiration is a metabolic process that generates energy. Plants can breathe in one of two ways, depending on the amount of oxygen they consume. Along with the oxidative breakdown of organic reserves into simpler molecules like CO_2 and water, aerobic respiration releases energy. Anaerobic respiration produces ethanol by decarboxylating pyruvate to CO_2 without the use of oxygen during fermentation metabolism. Anaerobic respiration is undesirable due to the unpleasant Odor created by the large amounts of ethanol, acetaldehyde, and other compounds that accumulate during the storage of F&V. Therefore, one key strategy for reducing loss and preserving quality during the postharvest ripening processes is to regulate respiration [4].

Fruits and vegetables remain alive even after harvest. Because of this, transpiration is often the main cause of postharvest loss; but, in humid regions where transpiration is low, respiration may become more important. Increased respiration leads to increased consumption of nutrients, which accelerates aging and reduces the shelf life of fruits and vegetables [13].

Throughout the ripening and storage phases, banana fruit experienced a variety of physiological, biochemical, and nutritional quality changes. One such process is enzymatic browning, which breaks down starch into simpler sugars. The sugar content of fresh pulp green banana fruit ranges from 1% to 2%, up to 20% as it ripens. Citric and malic acids work together to give the green (unripe) banana fruit its acidity. Furthermore, the texture of banana fruit changes as it ripens, which directly affects the fruit's quality. The concentration of pectin and the softening of bananas are strongly correlated. As pectin polysaccharides become more soluble, banana hardness diminishes [14].

The main objectives of this study were to estimate the oxygen consumption and CO_2 production and their effect on the respiration rate and ventilation rate in the fruit ripening for modelling of respiration rate and energy balance of bananas storage duration. Also, the study examined the economic impact during bananas storage.

MATERIALS AND METHODS

Three banana ripening models were used in the experiment, which was carried out in the city of Santa, Gharbia Governorate, between July 2024 and September 2024 for the summer and November 2023 to December 2023 for the winter. To estimate the amount of respiration heat and amount of O_2 consumption and CO_2 production released by banana and their effect on the respiration rate and Ventilation Rate in the fruit ripening models. The three rooms were equipped with a cooling and air conditioning unit, a ventilation and humidity control system, and gas distribution devices. Electricity, ethylene, supervisors, and maintenance workers were used.

The production capacity

Model 1 reached 12 tons with dimensions of (6 m length x 4 m width x 3 m height),

Model 2, which was 5 m in length, 4 m in breadth, and 3 m in height, weighed 8 tons and

Model 3 weighed 6 tons and measured 3 meters long by 4 meters wide by 3 meters high.

Measurements and determinations

Respiration Rate as a Function of Temperature in Banana Ripening rooms

Calculating the respiration rate of bananas in ripening refrigerators involves understanding the physiological processes that lead to the release of carbon dioxide (CO_2), consumption of oxygen (O_2), and the production of heat [6].

Respiration Rate for Oxygen Consumption (R_{O2})

$$R_{O_2} = \frac{V_{mo} \times G_{O_2}}{K_{mo} + (1 + \frac{G_{CO_2}}{K_{io}}) \times G_{O_2}} \quad (1)$$

where:

V_{mo}:Maximum oxygen consumption respiration rate (mg O_2/kg·h).

K_{mo}: Michaelis constant for O_2, (kPa).

K_{io}: Inhibition constant for O_2, (kPa).

G_{O2}: O_2 partial pressure in the room, (kPa).

G_{CO2}: Partial pressure of CO_2, starting (kPa).

Respiration Rate for CO_2 Production (R_{CO2})

$$R_{CO_2} = \frac{V_{mc} \times G_{O_2}}{K_{mc} + (1 + \frac{G_{CO_2}}{K_{ic}}) \times G_{O_2}} \quad (2)$$

where:

V_{mc}: Maximum respiration rate for CO_2 consumption, (mg CO_2/kg·h).

K_{mc}: Michaelis constant for CO_2, (kPa).

K_{ic}: Inhibition constant for CO_2, (kPa).

The respiratory quotient (RQ)

$$RQ = \frac{R_{O_2}}{R_{CO_2}} \quad (3)$$

Temperature-Dependent Respiration Rate (R_m)

$$R_m = R_p \times e^{-(\frac{E_a}{RT})} \quad (4)$$

where:

Rp: Baseline respiration rate, (mg CO_2/kg·h)

E_a: Activation energy (J/mol)

R: Universal gas constant, (8.314 J/mol·K).

T = Absolute temperature (K)

Ventilation Rate

$$\text{Ventilation Rate} = \frac{\text{Heat production rate during respiration } (kJ/kg \cdot h)}{\text{Target } CO_2 \text{ concentration} (g/m3)} \quad (5)$$

Heat Production During Respiration

The heat generated by the respiration process is critical for ripening and cooling system design:

$$Q = R_m \times H \quad (6)$$

where:

Q = Heat production rateduring respiration (kJ/kg·h)

H = Heat of respiration (0.44 W per mg CO_2/kg/h) for bananas.

The energy balance

The energy balance equation for a fruit ripening room helps in determining the energy input and output required to control the room's temperature, humidity, and airflow [21] can be calculated as follows:

$$\boldsymbol{Q_{in} = Q_{out} + Q_{storage}} \quad (7)$$

where:

Q_{in}: Energy entering the room, such as heating, cooling, respiration heat from the fruit, and other inputs (W).

Q_{out}: Energy lost through walls, windows, ventilation, and other exits (W).

$Q_{storage}$: Change in internal energy storage, accounting for heat stored in fruit mass and room structure (W).

Heat Addition (Q_{in}):

$$\boldsymbol{Q_{in} = Q_{heating} + Q_{respiration} + Q_{ventilation}} \quad (8)$$

where:

$Q_{heating}$: External heating system input, essential for maintaining room temperature, typically 5-10 kWh per ton of fruit per day.

$Q_{respiration}$: Heat generated from the ripening process, typically around 3-5 W/kg depending on the fruit type and stage of ripening

$Q_{ventilation}$: Energy from ventilation systems, if necessary to control gas concentrations (like ethylene) and remove heat from respiration. can be calculated as:

$$\boldsymbol{Q_{ventilation} = v \times \rho \times C_P \times \Delta T} \quad (9)$$

where:

ρ: air density (1.2 kg/m³).

Cp: specific heat of air (1.005 kJ/kg).

v: air flow rate (m³/s).

ΔT: difference between outside air temperature and room temperature.

Heat Loss (Q_{out}):

$$\boldsymbol{Q_{out} = Q_{conduction} + Q_{infiltration} + Q_{radiation}} \quad (10)$$

$$\boldsymbol{Q_{conduction} = A \times U \times \Delta T} \quad (11)$$

$$\boldsymbol{Q_{infiltration} = \frac{ACH \times V \times \rho \times C_P \times \Delta T}{3{,}600}} \quad (12)$$

where:

$Q_{conduction}$: Heat lost through walls, floors, and ceilings.

$Q_{infiltration}$: Heat lost due to air leakage, which can be significant if doors are frequently opened or if insulation is poor.

$Q_{radiation}$: is Radiation heat Losses and sometimes neglected in insulated ripening rooms.

A: a surface area (m²)

U: thermal conductivity (W/m²°C)

V: room volume (m³)

ACH is air changes per hour.

3,600 is the number of seconds in an hour to convert the flow rate into m³/s.

Internal Storage ($Q_{storage}$):

$$Q_{storage} = m \times C_P \times \Delta T \quad (13)$$

where:

m: Mass of fruit in the room (kg).

Cp: Specific heat capacity of the fruit, typically around ranges from 3.6 to 4.0 kJ/kg°C, depending on moisture content.

RESULTS AND DISCUSSIONS

Respiration Rate as a Function of Temperature in Banana Ripening models

The respiration rate for carbon dioxide production and oxygen consumption, respiratory quotient, temperature-dependent respiration rate, ventilation needs, and heat load of banana respiration prior to, during, and following ripening in the three ripening models are displayed in Figures 1, 2, 3, 4, and 5.

For green bananas, oxygen consumption and carbon dioxide production were at their lowest, with values for Model 1 of 11.28 mg O_2/kg/h and 10.46 mg CO_2/kg/h, Model 2 of 9.97 mg O_2/kg/h and 9.08 mg CO_2/kg/h, and Model 3 of 9.41 mg O_2/kg/h and 8.29 mg CO_2/kg/h.

As bananas begin to ripen, oxygen consumption and carbon dioxide production increase, with values for Model 1 being 30.94 mg O_2/kg/h and 36.27 mg CO_2/kg/h, Model 2 being 27.06 mg O_2/kg/h and 30.81 mg CO_2/kg/h, and Model 3 being 22.81 mg O_2/kg/h and 24.32 mg CO_2/kg/h.

At full ripening stage, oxygen consumption and carbon dioxide production decrease but are higher than the values for green bananas. The values for Model 1 were 21.32 mg O_2/kg/h and 20.85 mg CO_2/kg/h; Model 2 were 19.83 mg O_2/kg/h and 18.93 mg CO_2/kg/h; The model 3 was 18.06 mg O_2/kg/h and 16.72 mg CO_2/kg/h.

Thus, the respiration quotient (the balance between CO_2 production and oxygen consumption) of model 1 is about 0.93, 1.17 and 0.39; of model 2 is about 0.91, 1.14 and 0.95; and of model 3 is about 0.88, 1.06 and 0.93 for green, ripe and fully ripe bananas, which is a dimensionless ratio.

The temperature-dependent respiration rate is highest in ripe bananas at about 187.656, 113.225 and 76.802 g CO_2/kg/h in the three models, respectively. As for the ventilation requirements, they are determined by the balance between ethylene application and removal, as well as the respiration rates of bananas.

For the largest model 1 (72 m³), the lowest ventilation rates for green bananas were estimated due to the lowest respiration rate, with values of 2.53, 1.52 and 1.03 m³/h for the three ripening models.

As for the respiration heat, it decreases with decreasing temperature in the three models and as the ripening process continues, with values of 82.14, 49.56 and 33.61 kW at the full ripening stage, respectively.

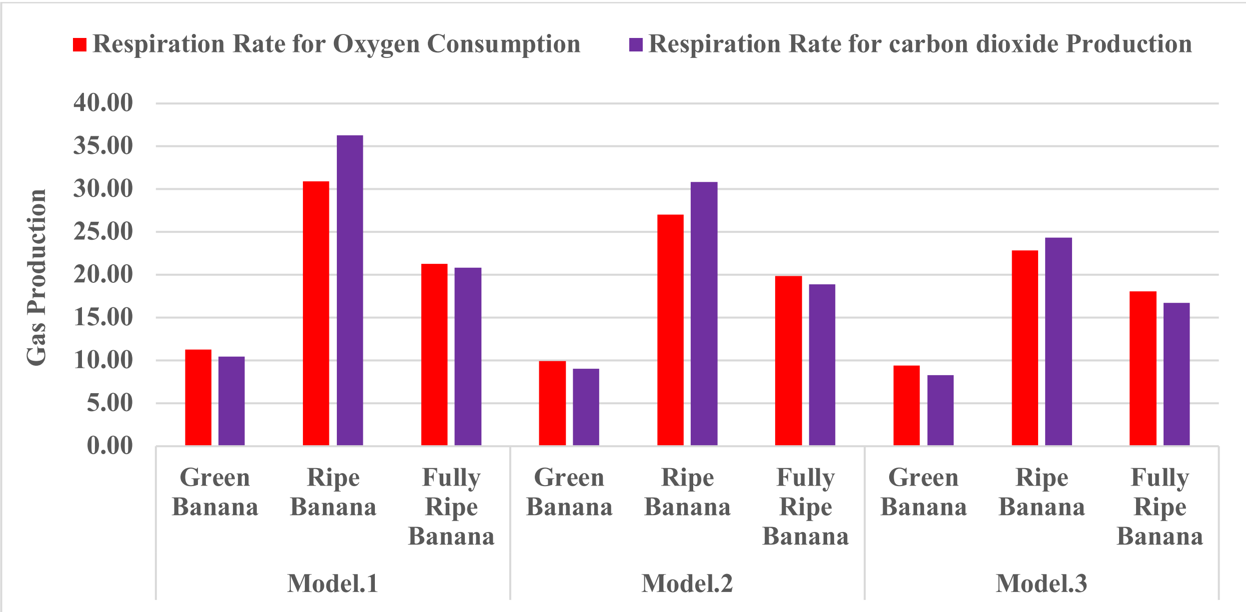

Fig. 1. The respiration rate for O_2 consumption and for CO_2 production of banana fruits in the three ripening models
Source: Authors' determination.

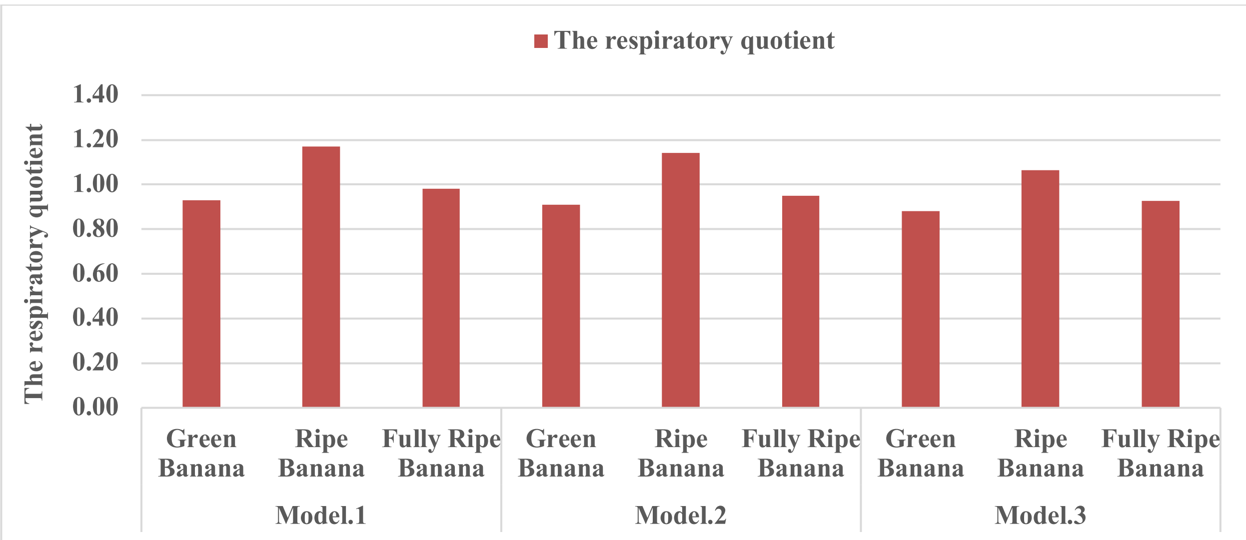

Fig. 2. The respiratory quotient of banana fruits using the three models for ripening
Source: Authors' determination.

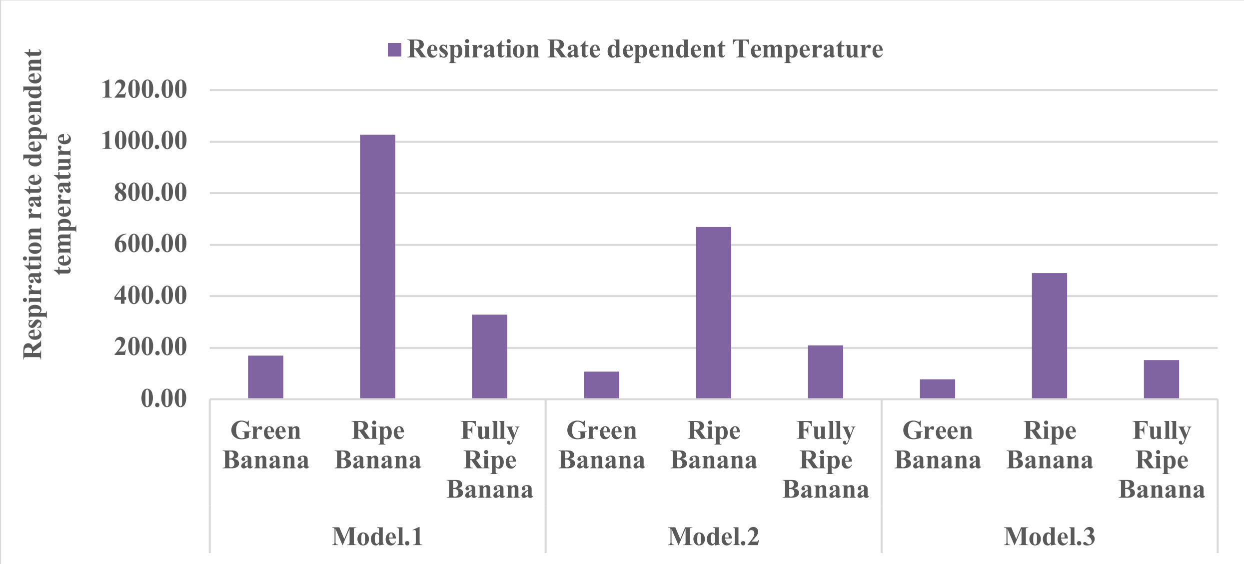

Fig. 3. Respiration Rate Dependent Temperature of the three ripening models for banana fruits
Source: Authors' determination.

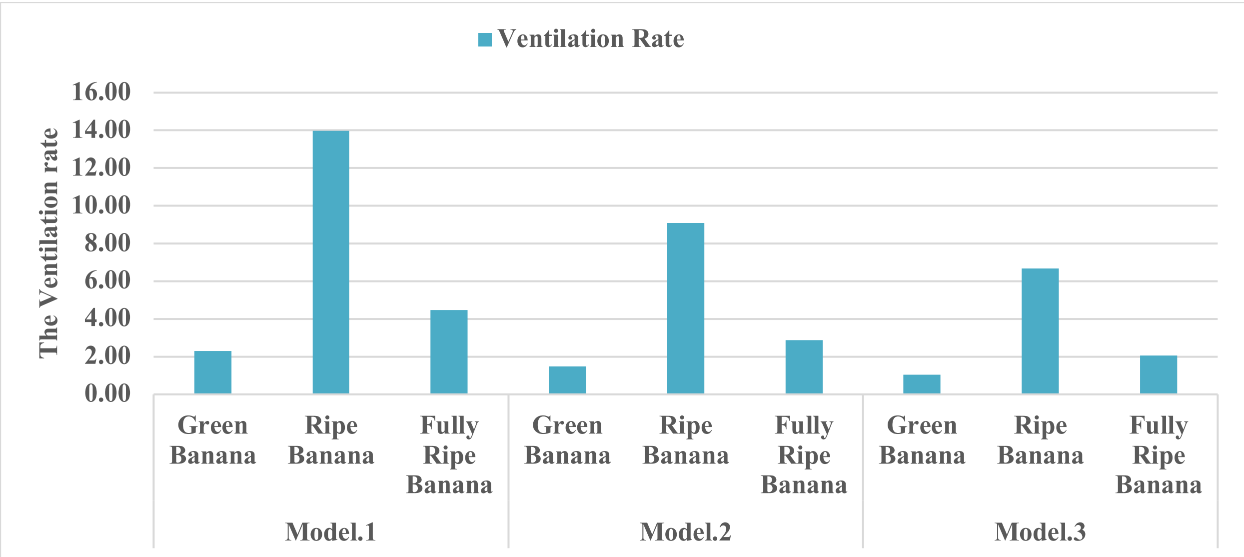

Fig. 4. The Ventilation Needs in the three ripening models
Source: Authors' determination.

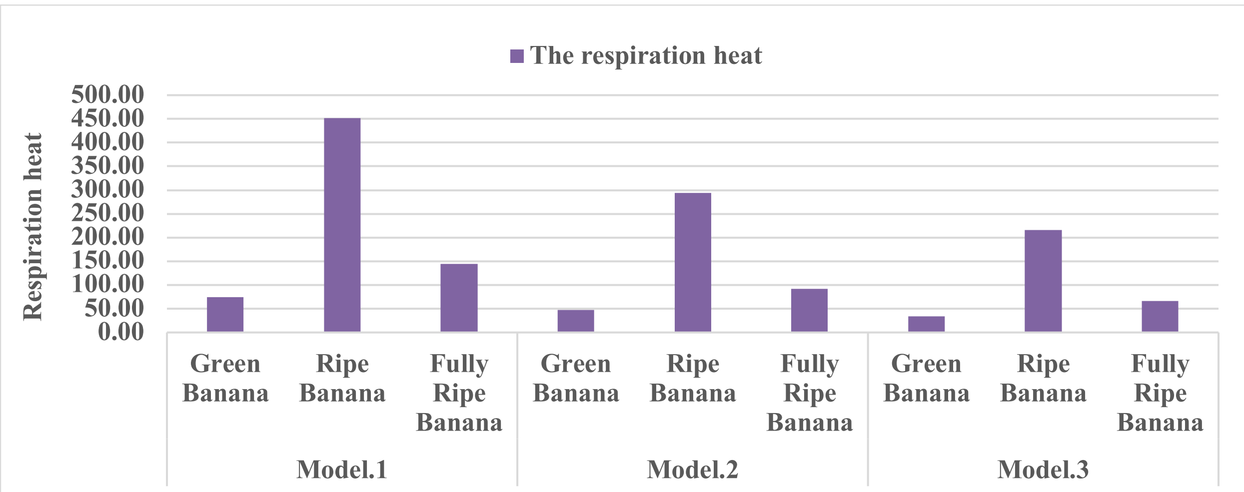

Fig. 5. The Respiration heat among the three models of ripening
Source: Authors' determination.

Energy balance

Figure 6 shows that the energy entering of the three ripening models in kW was compared to estimate the value of the energy entering generated by heating, cooling, ventilation, and lighting systems, and it was found that it has a direct relationship with the size of the model and an inverse relationship with the type of insulation, as the amount of energy entering decreases with the shrinkage of the model size, while it increases with the change in the type of insulation.

For 1,000 kg of bananas in models 1 and 2 insulated with cement, the energy entering decreases from 20.469 to 15.762 kW due to the small size of the model, while it increases in the third model insulated with ceramic to 11.799 kW due to the change in the type of insulation. Also, the energy entering for 10,000 kg of bananas decreases from 91.276 to 85.078 kW, respectively, in models 1 and 2 insulated with cement, while it increases to 88.967 kW in the third model insulated with ceramic.

Figure7 shows that the type of the size of the model affects the amount of energy lost through walls, windows, ventilation, and other exits. As the room size increases, the lost energy increases. In model 1, the lost energy was 14.192 kw because it is the largest area, and it decreased to 8.441 kw in model 2, and then reached 3.224 kW in model 3 because it is the smallest area.

Figure8 shows that the change in the internal energy storage of banana fruits in the three ripening models was compared, which changes with the change in the temperature of the fruits and the mass of the fruits.

For 1,000 kg of bananas in the three models, the values were 6.617, 7.194 and 8.222 kw, respectively. As for 10,000 kg of bananas, the values were 61.667, 71.944 and 82.222 kw, respectively.

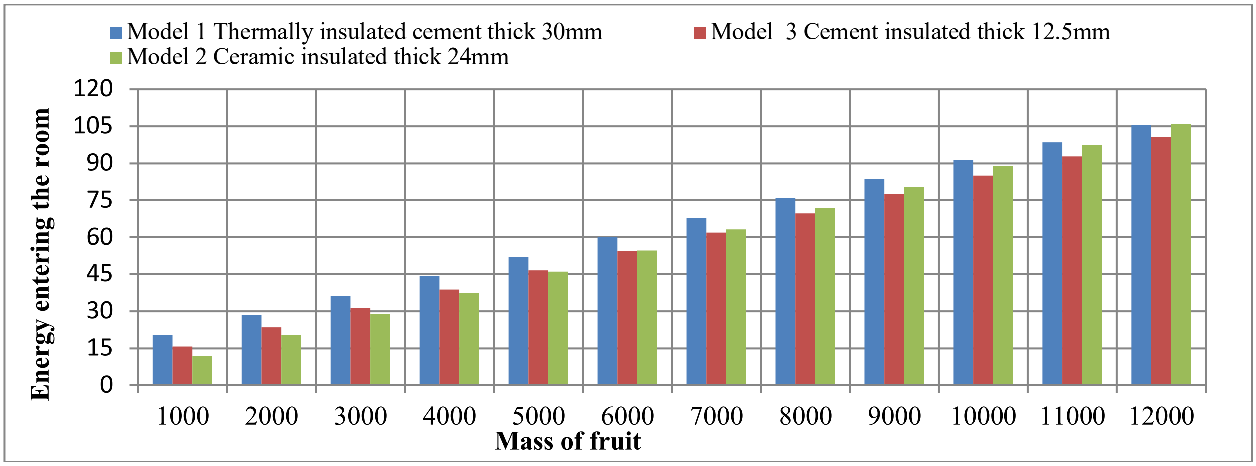

Fig. 6. Energy entering for the three modes of ripening
Source: Authors' determination.

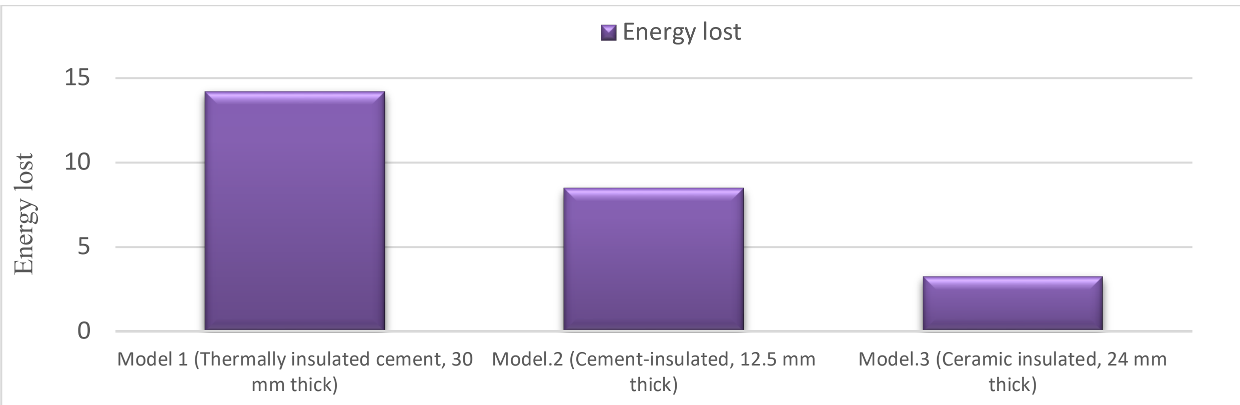

Fig. 7. The Energy loss for the three ripening models
Source: Authors' determination.

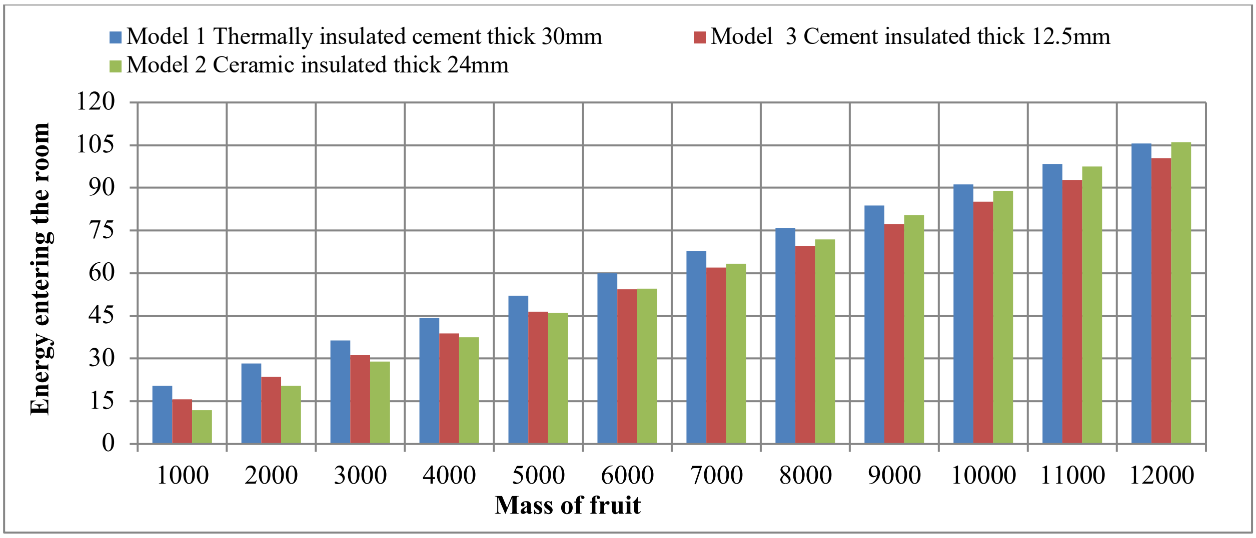

Fig. 8. The three ripening models' effects on the internal energy storage of banana fruits
Source: Authors' determination.

Economic impact of the three tested models during banana storage

Figures 9 and 10 show the relationship between total investment costs (EGP) and actual and approximate total monthly operating costs (in EGP). Investments were made at values lower than the approximate costs by about 58,000 EGP, 47,700 EGP, and 25,000 EGP in the third rooms, respectively. Operating costs were spent at values lower than the approximate operating costs by about 4,400, 3,000, and 1,700 EGP in the third rooms, respectively.

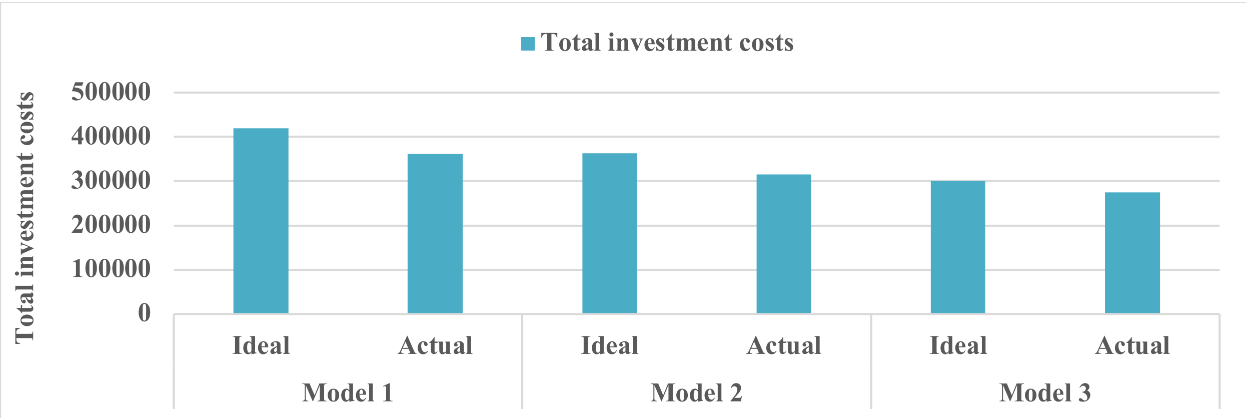

Fig. 9. The relationship between actual and approximate total investment costs in the three ripening models
Source: Authors' determination.

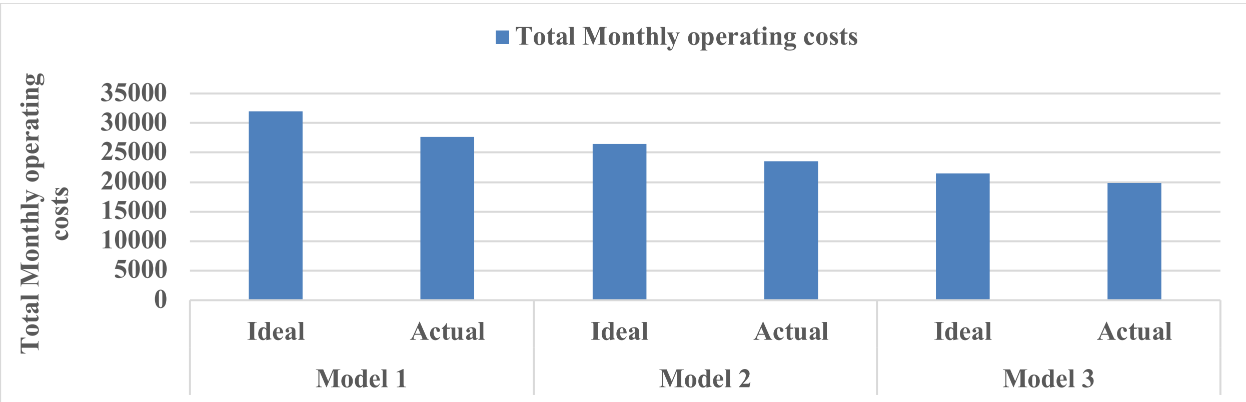

Fig. 10. The relationship between actual and approximate total monthly operating costs in the three ripening models
Source: Authors' determination.

CONCLUSIONS

The results showed that the respiration rate in bananas depends on their ripening stage and storage temperature, where metabolic processes, oxygen consumption (O_2) and carbon dioxide production (CO_2) are low in green bananas, then gradually increase to their highest levels with the onset of ripening and then decrease again with the progress of ripening, and ventilation and temperature requirements increase with the increase in respiration rate.

Therefore, it is necessary to control the temperature and air flow and prevent the accumulation of gases in the ripening rooms to maintain the quality of bananas and extend their storage life.

Otherwise, it could be registering quantitative losses and also the bananas will be of a lower quality.

In this way banana market offer will suffer and consumers as well, because they will not buy bananas of a lower quality.

The bananas of a lower quality will have to be sold at a lower price or transformed in wastes, and as a result the ripeners will diminish their income.

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