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BANANAS RIPENING MODELS IN A COOLING SYSTEM: COEFFICIENT OF PERFORMANCE, DIFFUSION FLUX OF ETHYLENE AND ECONOMIC IMPACT

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Abstract

The aim of this study is to determine the rate of ethylene diffusion and the heat load that the cooling system must handle and its effect on the coefficient of performance (COP). In this investigation, we experimented three banana ripening models in the Gharbia Governorate's city of Santa between December 2023 and January 2024. Model 1 was 72 m³ with thermally insulated cement walls that were 30 mm thick; Model 2 was 60 m³ of cement walls that were also insulated, but they were 12.5 mm thick; and Model 3 had 36 m³ built with ceramic walls of 24 mm thick. The measurement indicators were the respiration heat of bananas (Qr), the external heat load (Qext), the cooling load in a banana refrigerator (Qc), the coefficient of performance (COP) and the rate of ethylene diffusion. The findings can be summed up as follows: the model size has a direct link with the respiration temperature, cooling load, and coefficient of performance (COP), and it has an inverse relationship with the ethylene diffusion rate, internal temperature, and external temperature. The economic impact of banana storage reflects an increase in accrued revenues and thus an increase in net profit.

Key words: *bananas, ripening, COP, respiration, heat and energy, molecular diffusion of ethylene, economic Impact*

INTRODUCTION

Bananas are a popular fruit that originated primarily in tropical and subtropical climates. Egypt produced 1.21 million tons of bananas in 2022. At an average yearly rate of 5.52%, Egypt's banana production grew from 101 thousand tons in 1973 to 1.21 million tons in 2022 [8].
Egypt exported $1.91M in bananas, making it the 70th largest exporter of bananas in the world. And Egypt imported $4.19M in bananas, becoming the 88th largest importer of bananas in the world. In 2023, it registered a slight increase year-on-year of 0.29%, totalling 19.17 million metric tons [7].
When it comes to climacteric fruits, quality cannot be maintained during marketing and storage, even though controlled atmospheric storage or low temperature storage can increase shelf life. Fruit quality can be preserved for long-distance domestic and international shipping, and the product's shelf life can be increased with appropriate post-harvest processing and storage practices [13].
Fruits that are stored at a lower temperature have a longer shelf life and less respiratory activity. After further research revealed that the gaseous composition plays a significant role in the fruits' longer shelf-life, the concept of a controlled atmosphere (CA) with low O_2 and high CO_2 content in the storage environment was developed for the long-term preservation of fresh fruits [20].
The efficiency of a machine is related to its coefficient of performance (COP), which is the ratio of the energy required (i.e., input) to generate the refrigerating effect to the heat removed (i.e., output) from the chilled body. The coefficient of performance, or COP, is the quantity of heat that a thermoelectric

refrigerator can generate for every unit of electrical power supplied [10].

The performance of any process or device can be computed by dividing the intended impact by the production cost. The compressor's work input in the Reversed Carnot Cycle is the cost of achieving the desired result, which is the heat absorbed from the low-temperature heat source, also known as the refrigerating effect. The Reversed Carnot Cycle's prior performance metric was the Coefficient of Performance (COP) [14].

Damage to bananas may result from improper handling and ripening methods. The losses can show up at different points in the fruit supply chain. Harvesting and pre-harvesting could be discussed first, followed by marketing, packing, processing, storage, and transportation. Numerous writers investigated the factors that influence banana weight and quality losses and suggested methods to lower them along the supply chain [16,15, 1,11,2].

Post-ripe fruits are usually chosen at a low level of maturity because their storage life is limited when fully ripe. But the fruit is inedible since it is hard and has few soluble solids. Therefore, for fruit to become edible, it must ripen, either naturally or artificially. Customers have issues with the fruit's natural ripening process, including a lengthy ripening period and subpar flavour quality. For peeled and post-ripe fruits, postharvest ripening is therefore crucial. The foundation of ripening technology and essential components of the fruit supply chain are temperature regulation and gas conditioning. Direct ethylene ripening is currently one of the most popular ripening methods. This method was used in the past to speed up the metabolic process and significantly alter the characteristics of the internal components. Ripening can be efficiently hastened using 100 ppm ethylene at 20–23 °C by regulating the amounts of ethylene, CO_2, and O_2 [21].

It is common for fruit companies to place the ethylene generator in the storage area, operate it for ten hours or so, and then let the ethylene gas to exhaust itself. Ripening storage is then maintained between 17 and 20 °C. The temperature and humidity are then manually adjusted to allow the fruit to mature. For post-ripe fruits, precise ethylene monitoring during ripening is required. The ripening effect is influenced by temperature, CO_2, ethylene, and other factors. Temperature and ethylene content are the two most crucial variables [9].

One of the most significant fruits in the world is the banana. It is regarded as a good source of energy because of its high carbohydrate content. It has a distinct PR climacteric phase following harvest since it is a climacteric fruit. Because of its low respiration rate and low degree of ethylene production, the fruit does not ripen during this time. As the temperature drops between 40 and 15°C, this time frame may lengthen. The fruit's respiration rate rises after this time. This rise is strongly linked to the evolution of ethylene, the breakdown of peel chlorophyll, the conversion of starch to sugar, and the softening of pulp. The shelf-life of banana fruit is double and the processing duration is prolonged when it is ripened at a low temperature (15°C) [17].

In the ripening chamber, fruits treated with ethylene gas were kept for 36 hours at 200°C and 85–90% relative humidity. There were notable changes in the fruit's colour, going from green to yellow. In contrast, the chemical parameters TSS, reducing sugar, and total sugar exhibited an increasing tendency as concentration and post-treatment duration increased. As the ripening process progressed and the concentration of ethylene gas and ethephon grew, titratable acidity steadily reduced. The ethylene gas-treated fruits displayed less acidity. It was found that the physiological loss in weight (PLW) rose with storage duration, up to eight days in ambient conditions, irrespective of therapy. Banana fruits treated with 150 ppm ethylene gas showed the highest PLW in comparison to other treatments. Higher amounts of ethylene gas have been found to accelerate the ripening of bananas. The sensory score for banana fruits treated with ethylene gas increased significantly on the fourth day of ripening, indicating that the maturing banana fruits were favourably received. The safest method for ripening bananas is to use a cheap ripening chamber with 150 ppm ethylene gas for 36 hours at 200°C and 85–90% relative humidity [22].

Ethylene (ET) is a phytohormone that is crucial for regulating plant responses to stress. Numerous other plant traits that are critical to crop productivity and nutritional value are also under its control. ET has long been thought to be a ripening hormone in climacteric fruit. The functions of different ET generation and signalling components during the ripening process have been the subject of numerous studies. According to recent studies, heat stress (HS) dramatically reduces fruit output, quality, and postharvest stability by changing the regulation of several ethylene biosynthesis and signalling genes and interfering with fruit ripening. The relationship between ET, ripening, and HS remains unclear despite the tremendous advancements made in this field in recent years [19].

It takes time and specialized gas analysis equipment to measure the gas composition and produce respiration rate at a certain storage temperature. Many mathematical models have been developed to relate the respiration rate to different storage properties, including temperature and gas composition (e.g., O_2 and CO_2). The more recent technique for approximating respiration rate using the Michaelis-Menten type equation is based on enzyme kinetics. 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 [3].

Autocatalytic ethylene production and respiration both rapidly increase as climacteric fruits, like bananas, ripen. Since external ethylene causes ripening and suppression of its synthesis stops it, ethylene is regarded as the trigger in these fruits. They discovered that two important elements in the control of ethylene production seem to be the availability of ACC (1-aminocyclopropane-1-carboxylic acid) and the tissue's capacity to convert ACC to ethylene [4].

In apples and other fruits including avocado, banana, and tomato, the ethylene production pathway was clearly seen. When fruit begins to ripen, several ACC synthesis genes become active, increasing the amount of ACC produced. ACC oxidase subsequently converts this ACC to ethylene.ACC synthase activity usually determines the rate of ethylene synthesis. Ethylene biogenesis is triggered in naturally ripening banana fruit by certain factors that control the aging process.

Protein synthesis inhibitors were used to increase ethylene synthesis, which meant that they had an impact on tissue-level ripening equilibrium mechanisms. In actuality, the integrity of the cell membrane is frequently linked to the climacteric peak and the ability to produce ethylene. It's possible that a rigorous repair process that heavily relies on protein synthesis is what keeps the ethylene content in fruit tissues below its threshold level during fruit GL [6].

The banana fruit ripens in seven phases, and GL covers the first two. For the Cavendish cv., the CO_2 respiration is roughly 4 mg CO_2 $kg^{-1}.h^{-1}$, the sugar concentration is almost 0%, and the starch content is continuously high (23–25%). The only discernible characteristic of the green life stage is the peel's gradual change from deep green to green with a faint yellow hue due to a progressive decrease in chlorophyll.

Since starch hydrolysis does not occur during GL, we were unable to connect histological alterations like starch hydrolysis to variations in fruit GL. While the water-soluble tannin content of banana peel steadily declined during storage, particularly during ripening, the water-soluble tannin content of banana pulp first declined and subsequently increased during ripening [12].

Water stress actually increased the production of ethylene in pre-climacteric fruits, which led to an increase in respiratory metabolism, as seen in vegetative tissues. The fruit's autocatalytic ethylene production and the climacteric surge in respiration were probably caused by the ethylene that water stress created. Indeed, it is commonly known that storing fruits at low relative humidity (RH) accelerates water loss and causes early changes in respiration and ethylene production. Furthermore, it was observed that pulp and peel stored at high relative humidity showed a consistent increase in ACO activity [18].

The aim of this study is to determine the rate of ethylene diffusion, the heat load that the cooling system must manage, and how these factors affect the coefficient of performance (COP). Also, the study examined the economic impact during banana 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 and December 2023 for the winter.

To estimate the amount of metabolic heat released by the fruit as they respire and its effect on the energy balance in the fruit ripening models and thus on the Coefficient of performance (COP).With dimensions of 6 m length x 4 m width x 3 m height, the model 1's production capacity was 12 tons; the model 2's was 8 tons with dimensions of 5 m length x 4 m wide x 3 m height; and the model 3's was 6 tons with dimensions of 3 m length x 4 m width x 3 m height. as shown in Fig.1 and Fig. 2.

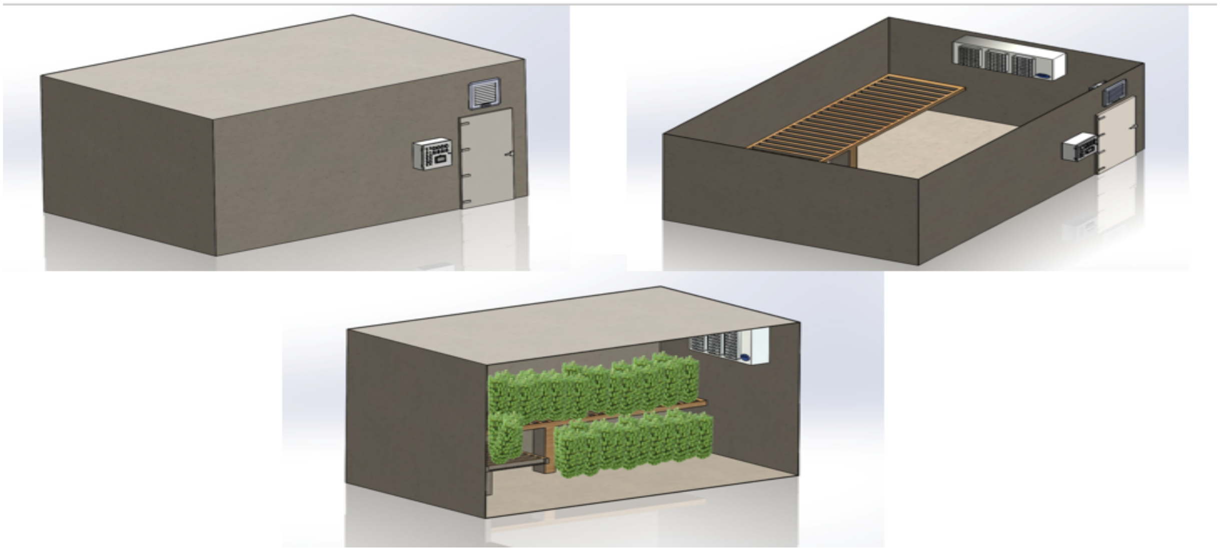

Fig. 1 Banana Ripening model
Source: Authors' determination.

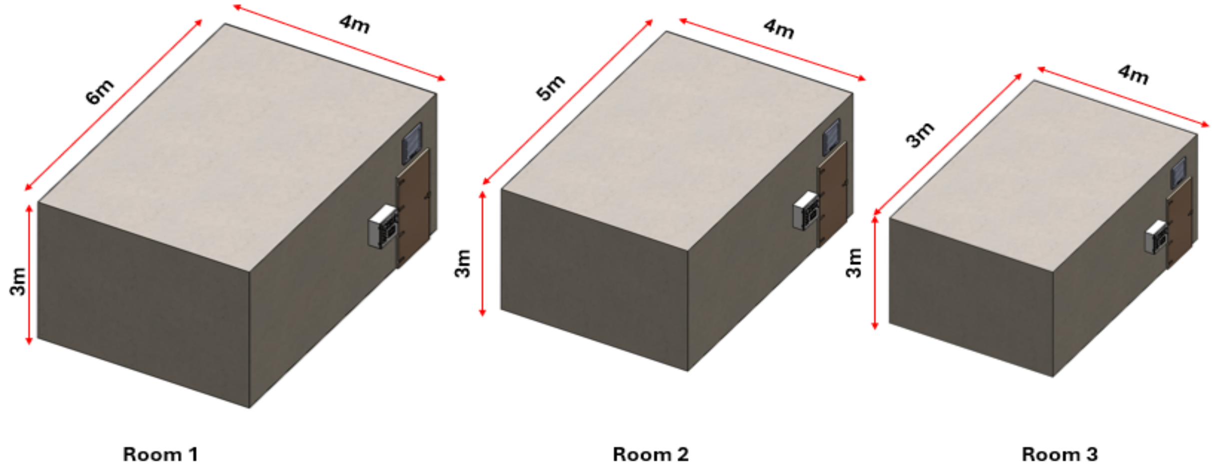

Fig. 2. Specifications of the Three Banana Ripening models
Source: Authors' determination.

Measurements and determinations
A set of mathematical equations was used to calculate the molecular diffusion of ethylene, respiration rate of banana fruit and the coefficient of Performance (COP)[20], which were calculated as:

-***Respiration Heat of Bananas***
Bananas, like other fruits, continue to respire after harvesting, producing heat and CO_2. The

rate of heat production due to respiration depends on the storage temperature and the maturity of the fruit. and can be calculated from:

$$\mathbf{Q_r = R \times H \times Massoffruit} \quad (1)$$

where:
Q_r is the respiration heat (W/kg or J/s).
R is the respiration rate of the banana (mg CO_2/kg/h)
H is the heat of respiration, which is typically around (0.44 W per mg CO_2/kg/h) for bananas.

-The external heat load

$$\mathbf{Q_{ext} = \frac{K \times A \times \Delta T}{d}} \quad (2)$$

where:
Q_{ext} is the external heat load (W).
k is the thermal conductivity (W/m·K). (for typical cement, k≈0.7 W/m.K). for ceramic k≈1.5 W/m.K).
A is the surface area of the walls (m²).
ΔT is the temperature difference between the outside and inside of the refrigerator (K).
d is the thickness of the cement wall (m).

-Cooling Load in a Banana Refrigerator

$$\mathbf{Q_c = Q_r + Q_{ext}} \quad (3)$$

where:
Qc is the total heat load
Qr is the heat generated by respiration.
Qext is the heat from external sources (which depends on the design of the refrigerator, insulation, ambient conditions, etc.).

-Coefficient of Performance (COP)

Once you have the cooling load and the work input, the COP can be calculated using the standard COP formula for cooling:

$$\mathbf{COP_{cooling} = \frac{Q_c}{W}} \quad (4)$$

where:
Qc is the total cooling load (in watts or joules per second), including respiration and other heat loads.
W is the work input, is the electrical energy consumed by the refrigeration system (in watts or joules per second).

The coefficient for Ethylene in Banana Ripening rooms

The coefficient of molecular diffusion D, governs the rate at which ethylene spreads throughout the ripening chamber by molecular motion. This process plays a critical role in the uniform ripening of bananas, since ethylene is the hormone responsible for triggering ripening [5].

***Fick's First Law*:**

This law gives us the flux of ethylene molecules moving through the air. It assumes steady-state diffusion, meaning the concentration gradient does not change with time. The equation is:

$$\boldsymbol{J = -\mathbf{D}\frac{dC}{dx}} \quad (5)$$

where:
J is the diffusion flux in mol/m²/s,
D is the diffusion coefficient of ethylene in air (m²/s)
C is the concentration of ethylene (mol/m³)
x is the distance along the diffusion path (m).
dC/dx is the concentration gradient (mol/m³).

The concentration of ethylene in the room

$$C = \frac{n}{V} \quad (6)$$

where:
C is the concentration of ethylene in moles per cubic meter (mol/m³)
n is the number of moles of ethylene (mol)
V is the volume of the room in cubic meters(m³)

***Volume of Ethylene Gas from Liquid*:**

To determine how much gas is produced from liquid ethylene, we can use the **ideal gas law** and density data.

$$\text{Mass of ethylene} = \text{Volume of ethylene} \times \text{Density of ethylene} \quad (7)$$

$$\text{Moles of ethylene gas (mol)} = \frac{\text{Mass of ethylene}}{\text{Molecular Weight}} \quad (8)$$

$$\text{Volume of ethylene gas (Lit)} = \frac{\text{Mass}}{\text{Molecular Weight}} \times 22.4 \quad (9)$$

where:

Density of liquid ethylene at its boiling point (-103.7°C) is (0.57 g/ml).
Molecular weight of ethylene (C_2H_4) = 28.05 g/mol
One mole of any gas occupies 22.4 L/mol.

The concentration gradient

$$\frac{dC}{dx} = \frac{C_{max} - C_{min}}{L} \quad \text{.........................} \quad (10)$$

where:
C_{max} is the concentration at the point closest to the ethylene generator
C_{min} is the concentration at the farthest point (near zero concentration)
L is Length the room

Diffusion Coefficient for Ethylene in Air

To estimate the diffusion coefficient for ethylene (C_2H_4) in air, we can use Fuller's equation:

$$D_{AB} = \frac{0.00143T^{1.75}}{P \times (M_{C_2H_4} + M_{air})^{0.5} \times (\sum\upsilon_{C_2H_4} + \sum\upsilon_{air})^2} \text{......} (11)$$

where:
D_{AB} is the diffusion coefficient of ethylene (cm²/s)
T is the temperature (Kelvin)
P is the pressure in atmospheres (atm)
M_{C2H4} and M_{air} are the molecular weights of ethylene (28.05 g/mol) and air (29.00 g/mol), respectively
$\sum\upsilon_{C2H4}$ and $\sum\upsilon_{air}$ are the diffusion volumes for ethylene (20.3) and air (20.1).

Energy Cost Calculation

$$\text{Energy Consumption} = \frac{\text{Power Usage (kW)}}{COP} \times \text{Operating Hours} \text{..........................} (12)$$

$$\text{Operating Hours} = 24 \text{ hours/day} \times \text{Ripening Duration} \text{..........................} (13)$$

$$\text{Total Cost} = \text{Energy Consumption} \times \text{Electricity Cost per kWh} \text{....................} (14)$$

Revenue Calculation

$$\text{Sellable Product} = \text{Total Load} \times (1 - \text{Percentage of Product Loss \%}) \text{...........} (15)$$

$$\text{Revenue} = \text{Sellable Product} \times \text{Market Price per Ton} \text{.......................} (16)$$

Net Profit Calculation

$$\text{Net Profit} = \text{Revenue} - \text{Energy Cost} \text{.......} (17)$$

RESULTS AND DISCUSSIONS

The concentration of ethylene

Fig. 3 shows the rate of ethylene diffusion in each of the three models. It was found that the size of the model affects the rate of ethylene diffusion. The rate of ethylene diffusion is slower in large rooms because the concentration is spread across a larger area. In all three models, the projected values ranged from 0.000039 to 0.000048 to 0.000111 mol/m².sec.

Coefficient of Performance (COP)

Fig. 4 shows that the type of insulation and the size of the model affect the amount of heat generated from the external thermal load. In models 1 and 2 which insulated with cement. The amount of heat generated from the external thermal load increases from 2.52 to 2.64 kw due to the small size of the model. While it increases in the third model insulated with ceramic due to the difference in the type of insulation, its value is 5.04 kw. As for the amount of heat generated from the internal thermal load, it increases from 0.65 kw in the first model to 0.95 in the second model and reaches the highest value in the third model insulated with ceramic to become 1.05 kw.
Fig. 5 shows that all three models show a clear positive correlation between banana weight and respiration heat. As banana weight increases, the generated respiration heat also increases linearly in all models. For Green bananas, the values were 74.833, 451.725 and 144.355 kw in the three ripening models, respectively; for ripe bananas, the values were 47.664, 294.329 and 92.482 kw; and for fully ripe bananas, the values were 33.64, 215.964 and 66.751 kw in the same three ripening models, respectively. Also shows that the type of insulation and the size of the model affect the cooling load. For Model.1, the values were 78.653, 455.545 and 148.175 kw for Green Banana, Ripe Banana, and Fully Ripe Banana, respectively; For Model.2, the values were 51.570, 298.235 and 96.388 kw for Green Banana, Ripe Banana, and Fully Ripe Banana, respectively; and for Model.3, the values were 39.730, 222.054 and 72.841 kw for three stages of banana ripening.

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Fig. 6 shows that cooling demand is directly related to temperature and volume, Increasing the size increases the thermal loads, requiring the compressor to work harder to maintain the internal temperature, thus increasing the coefficient of performance. The values of the coefficient of performance in Model 1 ranges from 4.916 to 5.2, in Model 2 from 4.77 to 5.1, and in Model 3 from 4.7.2 to 5, respectively.

Economic impact of the three tested models during banana storage

Fig. 7 shows the total costs, revenues and net profit for the three models over one cycle. It was found that the first model achieved the highest revenue, estimated at 234360 EGP, compared to the revenues of the other two models.

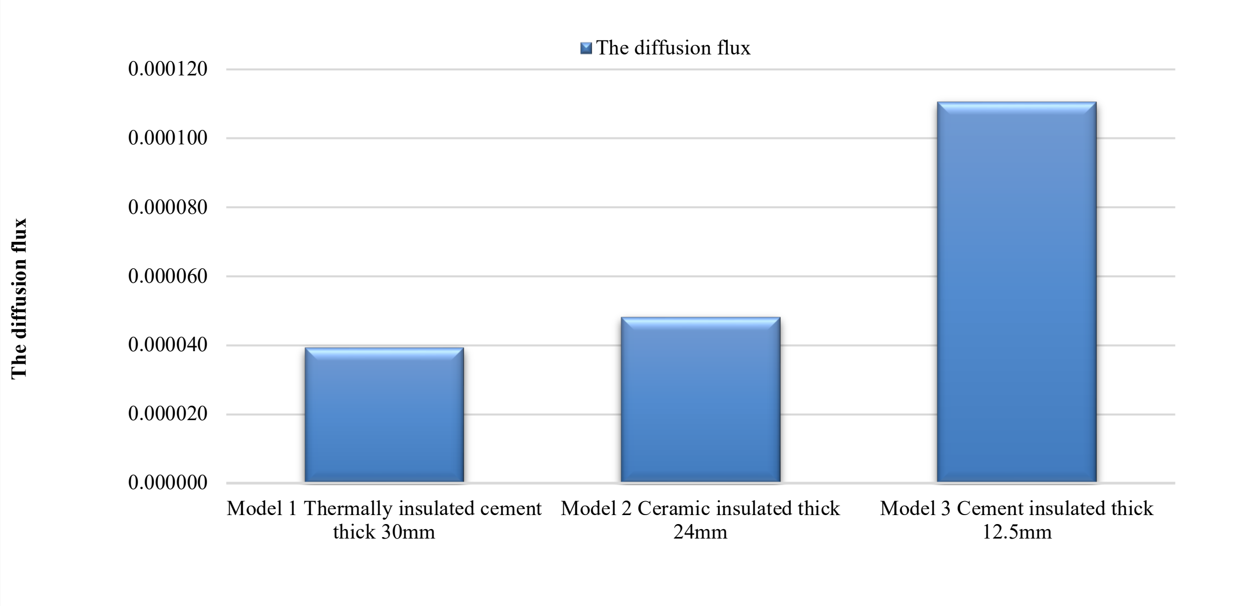

Fig. 3. The ethylene diffusion flux in the three ripening models
Source: Authors' determination.

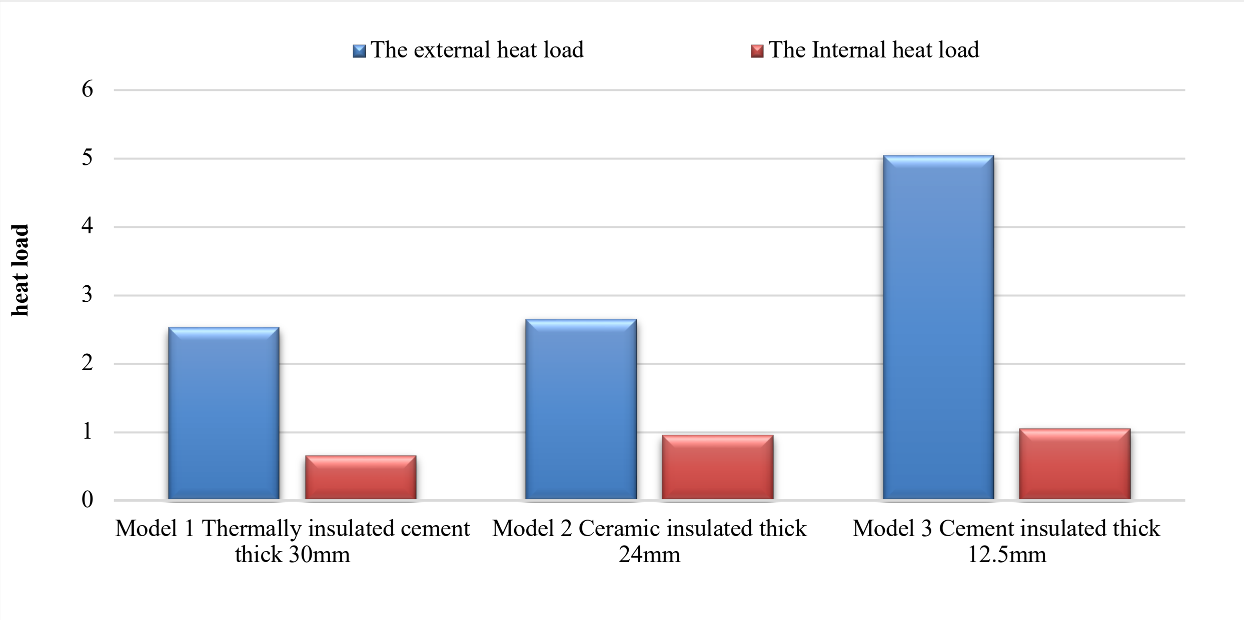

Fig. 4. Three ripening models' internal and exterior heat loads.
Source: Authors' determination.

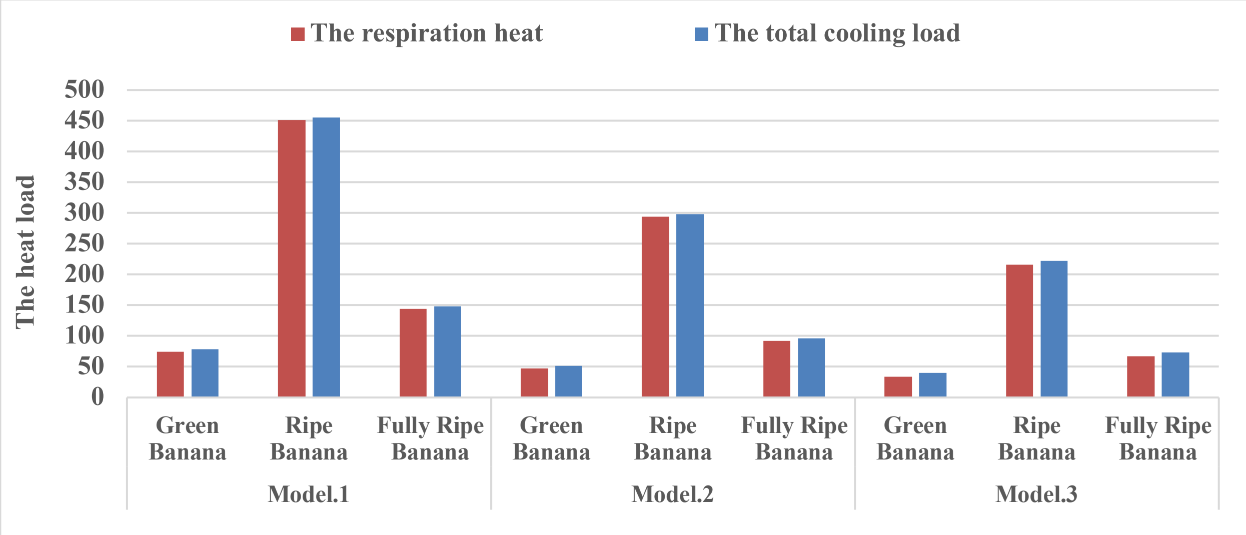

Fig. 5. Banana fruit respiration heat and overall cooling load in the three-ripening models.
Source: Authors' determination.

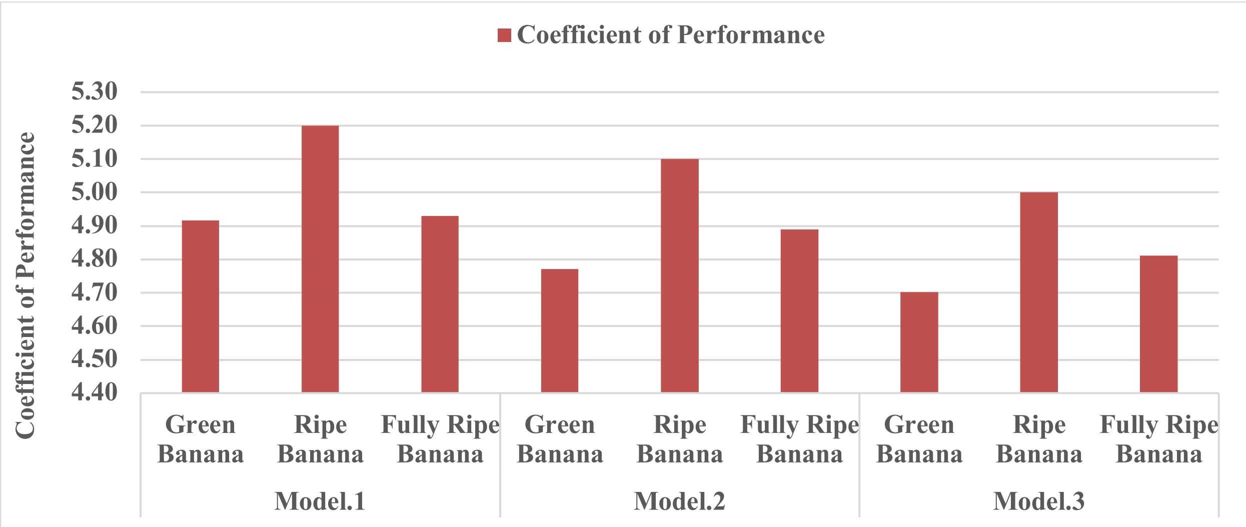

Fig. 6. The coefficients of performance for the three ripening models
Source: Authors' determination.

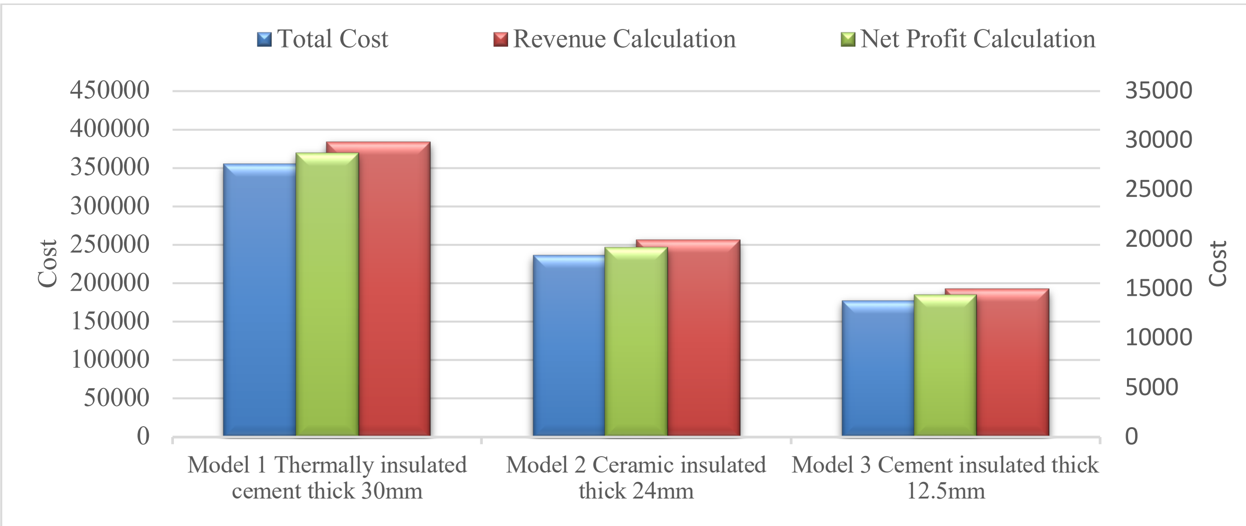

Fig. 7. The three ripening models' total expenses, total income, and total net profit
Source: Authors' determination.

CONCLUSIONS

The findings demonstrated that the three ripening models' measurements were substantially impacted by the models' sizes, temperature, and banana quantity, where the larger the quantity of bananas and the larger the room size, the higher the respiration rate and the greater the need for air cooling, and also the higher the temperature, the lower the energy consumption, which leads to an increase in the system efficiency (COP).In order to guarantee the quality of the finished product, enhance the models' operational efficiency, and extend the shelf life of ripe bananas while lowering losses during storage and transit, it is vital to keep an eye on temperature, humidity, ethylene gas concentration, and banana respiration temperature. And meeting market requirements and thus achieving sustainability and improving profitability. In short, the performance factor in banana ripening refrigerators plays a pivotal role in ensuring product quality, improving operational efficiency, and reducing costs, which benefits both producers and consumers.

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