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Temperature-Dependent Respiration Kinetics and Preliminary Shelf-Life Estimation of Namnam Fruit (*Cynometra cauliflora*)

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Abstract

Background: Postharvest deterioration of tropical fruits is strongly influenced by respiration activity, which is highly sensitive to storage temperature. However, respiration kinetics data for underutilized fruits, such as namnam (*Cynometra cauliflora*), remain limited, restricting the development of effective storage strategies.
Objective: This study aimed to analyze the effects of storage temperature on respiration kinetics and estimate the preliminary shelf life of namnam fruit using kinetic modeling approaches.
Method: Namnam fruits were stored at 10°C, 20°C, and 30°C and evaluated using a closed-system CO_2 absorption method with triplicate measurements. Respiration rates were analyzed using linear regression, the *Arrhenius* model, Q_{10} temperature coefficients, and a zero-order degradation model for shelf-life estimation.
Result: Respiration rates increased with increasing temperature, showing a strong linear relationship (R^2 = 0.9984). *Arrhenius* analysis yielded an apparent activation energy of 27.3 kJ mol^{-1} with a moderate model fit (R^2 = 0.6682). Q_{10} values ranged from 1.45 to 1.68, indicating moderate temperature sensitivity. The estimated shelf life decreased from 13.46 days at 10°C to 9.06 days at 20°C and 6.26 days at 30°C.
Conclusion: Lower storage temperatures effectively reduced respiratory activity and extended shelf life; however, respiration-based estimates should be validated using direct quality parameters before commercial application.

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INTRODUCTION

Cynometra cauliflora, commonly known as Namnam fruit, is a tropical fruit found in several Southeast Asian countries, including Indonesia and Malaysia. The fruit has a distinctive sour–sweet taste and is locally consumed; however, its wider utilization remains limited. Beyond market familiarity, one practical constraint is its short postharvest life. Namnam fruit deteriorates rapidly after harvest, while scientific information on its postharvest physiology, particularly its respiration behavior under different storage temperatures, remains scarce.

After harvest, fresh fruits remain metabolically active. Processes such as respiration, transpiration, ethylene-related metabolism, and enzymatic reactions continue even after the fruit

has been detached from the plant. These processes contribute to ripening, senescence, water loss, and changes in eating quality during storage (Lin et al., 2026; Saltveit, 2019). Among these processes, respiration is often used as a direct indicator of metabolic activity because it reflects the breakdown of organic substrates into carbon dioxide, water, and energy required for cellular maintenance. Fruits with high respiration rates generally have shorter storage lives because substrate depletion and metabolic deterioration occur more rapidly (Chang et al., 2026; Mahajan et al., 2009).

Respiration rate is therefore useful not only for describing physiological behavior but also for estimating storage potential. Quantitative respiration data can support decisions related to storage temperature, packaging design, and postharvest handling systems. In modified atmosphere packaging (MAP) or other controlled storage applications, for example, respiration data are required to balance gas exchange and prevent conditions that may accelerate deterioration or induce undesirable anaerobic metabolism (Conte et al., 2012; Ho et al., 2020; Maciel et al., 2026) However, such information is often unavailable for local or less-commercialized tropical fruits.

Temperature is one of the main external factors affecting fruit respiration. In general, higher storage temperatures increase biochemical reaction rates and accelerate metabolic activity, whereas lower temperatures suppress respiration and can delay deterioration (Chen et al., 2021; Ramzan et al., 2022). Nevertheless, the response of respiration to temperature is not always simple or strictly linear, particularly in tropical fruits that may have different physiological tolerances to low or high storage temperatures. Therefore, temperature-dependent respiration data are required for each commodity rather than relying solely on general assumptions derived from other fruits.

Mathematical models are commonly used to describe the relationship between temperature and respiration rate. The Arrhenius equation, for instance, has been applied to characterize temperature-dependent reaction kinetics and estimate the sensitivity of biological reactions to storage temperature (Brilliantina et al., 2022). Another commonly used parameter is the Q_{10} value, which describes the relative increase in reaction or respiration rate for every 10°C increase in temperature. These approaches have been applied in postharvest studies of several commercial fruits, including apples, bananas, strawberries, and mangoes (Brilliantina et al., 2022; Sari & Simbolon, 2020). More recent studies have also combined postharvest measurements with digital monitoring and data-driven models to improve the prediction of quality changes during storage (Thakur et al., 2026; Thakur et al., 2019; Zhu et al., 2015).

Most available respiration models, however, have been developed for fruits with established commercial value and well-documented postharvest systems. Information regarding less-studied tropical fruits remains limited. For Namnam fruit, previous studies have mainly focused on phytochemical composition, antioxidant activity, and potential medicinal properties. Data on respiration rate, temperature sensitivity, and storage-life estimation are still rarely reported. This lack of quantitative postharvest information makes it difficult to formulate handling recommendations for maintaining fruit quality after harvest.

Despite the growing interest in underutilized tropical fruits, quantitative postharvest data for Namnam fruit remain notably absent from the literature. No previous study has systematically characterized the respiration kinetics of *Cynometra cauliflora* under controlled temperature conditions or applied kinetic modeling to estimate its storage potential. This knowledge gap limits the development of evidence-based postharvest handling strategies for this commodity. To address this gap, the present study evaluated the effect of storage temperature on the respiration rate of *Cynometra cauliflora* stored at 10, 20, and 30°C. The study further examined respiration-derived kinetic parameters, including Arrhenius activation energy and Q_{10} values, for preliminary shelf-life estimation. The specific objectives were: (1) to quantify the respiration rates of Namnam fruit at three storage temperatures; (2) to characterize the temperature sensitivity of respiration using Arrhenius and Q_{10} models; and (3) to provide a preliminary estimate of respiration-based storage life. The results are expected to provide baseline information on the temperature-dependent postharvest behavior of Namnam fruit and support the further development of storage and handling strategies for this commodity.

METHOD

Research Framework

The study was designed to evaluate the respiration behavior of Namnam fruit (*Cynometra cauliflora*) under different storage temperatures and to use the resulting respiration data for preliminary shelf-life estimation. The research stages included fruit collection, sample selection, storage treatment, respiration measurement, kinetic analysis, and estimation of storage life. A schematic overview of the research procedure is presented in Figure 1.

Fruits with relatively uniform maturity, size, and physical condition were selected to reduce biological variation among samples. The selected fruits were stored at three temperature conditions, namely 10, 20, and 30°C. Respiration was measured using a closed system method, in which CO_2 released by the fruit was absorbed in sodium hydroxide solution and quantified by titration. The measured CO_2 production was then converted into respiration rate and expressed as mg CO_2 kg^{-1} h^{-1}. The respiration data were further analyzed using temperature–respiration regression, Arrhenius modeling, Q_{10} calculation, and a preliminary respiration-based shelf-life estimation approach.

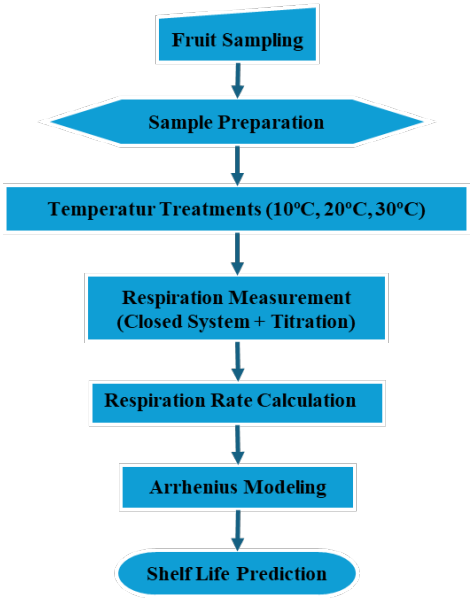

Figure 1. Research framework of respiration analysis and shelf-life prediction of Namnam fruit under different storage temperatures

Fruit Materials

Namnam fruits (*Cynometra cauliflora*) were collected from local trees in Jember Regency, East Java, Indonesia. The fruits were harvested at the half-ripe stage, determined based on external color and firmness. Only fruits with uniform size and without visible defects, mechanical injury, or disease symptoms were used in the experiment. After harvesting, the fruits were transported to the laboratory and handled carefully to minimize mechanical damage. The samples were gently cleaned to remove adhering dirt and foreign materials, sorted according to visual uniformity, and then randomly allocated to the storage temperature treatments.

Experimental Design and Storage Conditions

The experiment was arranged in a completely randomized design with three storage temperature treatments: 10, 20, and 30°C. Each treatment consisted of three replications, and each replication contained five fruits. The selected temperatures were used to represent low, moderate, and relatively high storage conditions for evaluating the temperature response of fruit respiration.

For respiration measurement, the fruits were placed in airtight containers to create a closed system that allowed the accumulation and absorption of respiratory CO_2 during a fixed incubation period. The containers were placed in temperature-controlled storage chambers

according to the assigned treatments. Respiration measurements were carried out at 12-hour intervals during storage.

Measurement of Respiration Rate

The respiration rate of Namnam fruit was determined using a closed system method combined with titration analysis. This method was used to quantify CO_2 released by the fruit during storage. For each measurement, fruit samples were placed in an airtight container for an incubation period of 1 hour. The CO_2 produced during respiration was absorbed using a known volume of sodium hydroxide (NaOH) solution.

After incubation, the remaining NaOH was titrated with standard hydrochloric acid (HCl), using phenolphthalein as an indicator. A blank titration was also conducted to determine the initial amount of NaOH before CO_2 absorption. The respiration rate was calculated using the following equation:

$$RR = \frac{(V_b - V_s) \times N \times 22}{W \times t}$$

Where $RR$is the respiration rate (mg CO_2 kg^{-1} h^{-1}), $V_b$is the volume of HCl used for blank titration (mL), $V_s$is the volume of HCl used for sample titration (mL), $N$is the normality of HCl, $W$is the weight of fruit sample (kg), and $t$is the incubation time (h).

The calculated respiration rate was used as the main physiological parameter to describe metabolic activity of Namnam fruit during storage.

Arrhenius Modeling and Q_{10} Calculation

The effect of temperature on respiration was evaluated using an Arrhenius-type model. In this study, the respiration-derived rate parameter was treated as an empirical indicator of temperature-dependent metabolic activity, rather than as a true elementary chemical reaction constant. This interpretation was used because fruit respiration represents a complex biological process involving several metabolic reactions.

The Arrhenius equation was expressed as:

$$k = k_0 \exp\left(\frac{-E_a}{RT}\right)$$

Where $k$is the respiration-derived rate parameter, $k_0$is the pre-exponential factor, $E_a$is the activation energy, $R$is the universal gas constant, and $T$is the absolute temperature in Kelvin. For parameter estimation, the equation was linearized as:

$$\ln k = \ln k_0 - \frac{E_a}{RT}$$

The activation energy was obtained from the slope of the linear regression between $\ln k$and $1/T$. Because the model was derived from observed respiration behavior, the estimated activation energy was interpreted as an apparent activation energy describing the temperature sensitivity of respiration.

The temperature sensitivity of respiration was also evaluated using the Q_{10} coefficient:

$$Q_{10} = \left(\frac{R_2}{R_1}\right)^{\frac{10}{T_2 - T_1}}$$

Where $R_1$and R_2 are respiration rates at temperatures $T_1$and T_2, respectively. The Q_{10} value represents the relative change in respiration rate associated with a 10°C increase in storage temperature.

Preliminary Shelf-Life Estimation

Shelf-life estimation was carried out using a respiration-derived quality degradation approach. In this approach, the deterioration rate constant (k_d)was used as an empirical parameter representing the rate of quality decline associated with metabolic activity during storage. A zero-order degradation assumption was applied to estimate storage life:

$$t_s = \frac{Q_0 - Q_t}{k_d}$$

Where t_s is the estimated shelf life, $Q_0$is the initial quality index, $Q_t$is the threshold quality index at the end of acceptable storage, and $k_d$is the respiration-derived deterioration constant.

The value of Q_0 was assumed to be higher than Q_t, representing a decline in quality during storage. Since the deterioration constant was derived from respiration behavior, the resulting shelf-life values were interpreted as preliminary indicators of metabolic deterioration. They were not treated as direct commercial shelf-life limits because direct quality attributes, sensory rejection points, and marketability thresholds were not measured in this study.

Statistical Analysis

All measurements were conducted in triplicate, and the data were expressed as mean values ± standard deviation. Descriptive statistics were used to summarize respiration rates at each storage temperature and time point. Linear regression analysis was performed to evaluate the relationship between storage temperature and mean respiration rate. Arrhenius parameters were estimated from the linearized relationship between ln k and $1/T$, and the goodness of fit was assessed using the coefficient of determination (R^2). The sequential connection between the research stages was as follows: respiration rates measured at each temperature served as inputs for linear regression modeling; the temperature–respiration relationship then provided the basis for Arrhenius and Q_{10} calculations; and the resulting kinetic parameters were subsequently used to derive deterioration constants for the zero-order shelf-life estimation model. Q_{10} values were calculated to describe the relative sensitivity of respiration rates to temperature changes between storage intervals. Shelf-life values were estimated using the zero-order respiration-derived degradation model. Since no independent validation dataset or direct quality threshold measurements were available, the shelf-life estimation was evaluated based on its consistency with the observed respiration trends and interpreted as a preliminary modeling framework.

RESULTS AND DISCUSSION

Results

The respiration rate of *Cynometra cauliflora* varied according to storage temperature and storage duration. As shown in Figure 2, CO_2 production increased during storage at all tested temperatures. The highest respiration rate was recorded at 30°C, followed by 20°C and 10°C. This result indicates that higher storage temperature increased the respiratory activity of Namnam fruit.

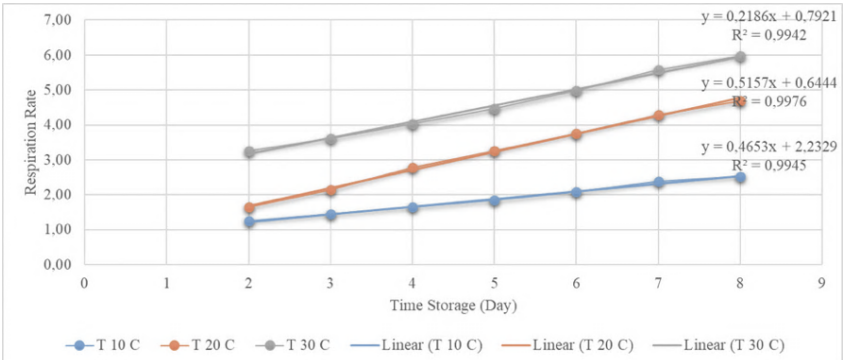

Figure 2. Respiration rate of Namnam fruit during storage at 10°C, 20°C, and 30°C

The respiration rate continued to increase throughout the observation period, indicating that the fruit remained physiologically active after harvest. No clear respiration peak was detected during the measurement period. Fruits stored at 30°C consistently exhibited the highest absolute respiration rate, whereas fruits stored at 10°C showed the lowest respiration rate throughout storage.

An interesting pattern was observed in the rate of increase over time. Although the highest absolute respiration rate occurred at 30°C, the increase in respiration rate appeared to be steeper at 20°C. This finding indicates that the respiratory response of namnam fruit was influenced not only by storage temperature but also by the physiological condition of the fruit during storage.

The relationship between storage temperature and respiration rate demonstrated a strong positive linear trend within the tested temperature range. The coefficient of determination was high, with an R^2 value of 0.9984, indicating that the respiration rate increased consistently as the storage temperature increased from 10°C to 30°C.

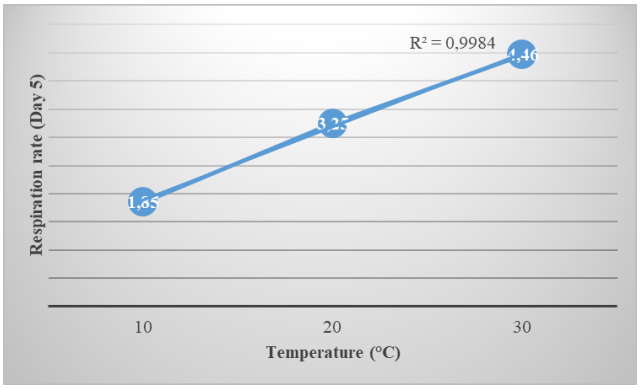

Figure 3. Linear relationship between storage temperature and respiration rate of namnam fruit, R^2 = 0.9984.

The Q_{10} values indicated that namnam fruit exhibited moderate temperature sensitivity. The calculated Q_{10} values were 1.68 for the 10–20°C interval and 1.45 for the 20–30°C interval. The decrease in Q_{10} at the higher temperature interval indicates that the proportional increase in respiration rate became lower as the temperature increased from 20°C to 30°C. This declining Q_{10} pattern is noteworthy because it deviates from the commonly reported range of 2–3 for many fresh horticultural commodities (Ghosh & Dash, 2020; Lin et al., 2026; Saltveit, 2019), suggesting that namnam fruit exhibits a comparatively restrained respiratory response to increasing temperature.

The Arrhenius relationship between the respiration rate constant and storage temperature is presented in Figure 4. The apparent activation energy estimated from the model was approximately 27.3 kJ mol^{-1}. The Arrhenius model showed a moderate coefficient of determination, with an R^2 value of 0.6682. This moderate model fit is consistent with findings by Rahayu et al. (2021) and Rahman and Faisal (2023), who reported that Arrhenius models applied to complex biological systems often produce lower R^2 values than those obtained from controlled chemical reactions due to the multi-pathway characteristics of fruit respiration (Hutabarat et al., 2026). The activation energy value falls within the range reported for other tropical fruits, such as fig (Ghosh & Dash, 2020) and banana (Rahman & Faisal, 2023), confirming that namnam fruit exhibits temperature-dependent but moderately sensitive respiratory kinetics (Lin et al., 2026).

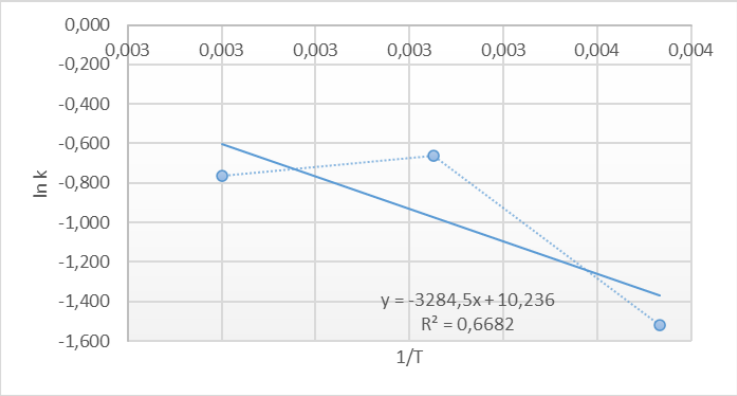

Figure 4. Arrhenius relationship between respiration rate constant and temperature in namnam fruit

The preliminary shelf-life estimation based on the zero-order respiration-derived degradation model is presented in Table 1. The estimated storage life decreased with increasing storage temperature. At 10°C, the estimated shelf life was 13.46 days. This value decreased to 9.06 days at 20°C and 6.26 days at 30°C.

Table 1. Respiration-derived kinetic parameters and preliminary shelf-life estimation of namnam fruit under different storage temperatures

Storage temperature (°C)	Deterioration constant, kd (index day^{-1})	Initial quality index, Q_0	Threshold quality index, Q_t	Estimated shelf life (day)
10	0.2541	6.36	2.94	13.46
20	0.3776	6.36	2.94	9.06
30	0.5467	6.36	2.94	6.26

Note: The initial quality index ($Q_0 = 6.36$) represented the quality condition of namnam fruit at the beginning of storage. The threshold quality index ($Q_t = 2.94$) represented the predetermined minimum acceptable quality level at the end of storage, corresponding to the maximum tolerable deterioration under the experimental conditions. Shelf life was defined as the time required for the quality index to decrease from $Q_0$to Q_t. The $Q_t$value was established from preliminary observations as the quality index corresponding to the final condition at which the fruit was still considered acceptable.

Discussion

The increase in respiration rate with increasing storage temperature demonstrates that temperature is a key factor controlling the postharvest metabolic activity of namnam fruit. Respiration is one of the primary physiological processes that continues after harvest because fruit tissues remain alive and require energy for cellular maintenance. During respiration, stored substrates such as sugars and organic acids are oxidized, producing CO_2, water, and energy. Therefore, higher CO_2 production reflects greater metabolic activity and faster depletion of internal reserves. This response is consistent with the general behavior of fresh horticultural commodities, in which elevated temperatures accelerate enzymatic reactions involved in glycolysis, substrate oxidation, and the tricarboxylic acid cycle (Lin et al., 2026; Saltveit, 2019).

The lower respiration rate observed at 10°C suggests that low-temperature storage was effective in reducing metabolic activity. Reduced respiration under low-temperature conditions is important because it can slow substrate depletion, delay senescence, and maintain postharvest quality for an extended period. In contrast, storage at 30°C resulted in the highest respiration rate, indicating more rapid metabolic turnover. Under warm storage conditions, cellular metabolism proceeds more rapidly, which may accelerate ripening-associated changes such as softening, conversion of reserve carbohydrates, pigment changes, aroma development, and eventual senescence. Although these quality attributes were not directly measured in the present study,

the respiration pattern suggests that deterioration processes would likely progress faster at higher temperatures.

The continuous increase in respiration rate during the observation period indicates that namnam fruit remained physiologically active throughout storage. This finding suggests that the fruit did not enter a metabolically inactive phase after harvest. Instead, the fruit continued to undergo postharvest metabolic processes associated with ripening and senescence. Similar increases in respiration during storage have been reported in several horticultural commodities, where respiration is closely associated with physiological deterioration and quality loss (Freitas et al., 2015; Ramzan et al., 2022; Sari & Simbolon, 2020; Yahia, 2011). However, the absence of a distinct respiration peak in this study should be interpreted carefully. A respiration peak is often used to identify climacteric behavior, but its absence within a limited observation period does not necessarily indicate that namnam fruit is non-climacteric. The peak may have occurred before the first measurement, after the observation period, or may have been obscured by the selected sampling interval. Therefore, ethylene measurement and longer storage observations are required to clearly determine whether namnam fruit exhibits a climacteric or non-climacteric respiration pattern.

The temporal respiration pattern also provides important physiological insights. Although fruits stored at 30°C showed the highest absolute respiration rate, the increase in respiration rate over time was steeper at 20°C. This indicates that the fruit response was not purely linear with time or solely determined by temperature magnitude. At 30°C, the fruit may have experienced a high initial metabolic load, resulting in rapid substrate consumption or the earlier onset of physiological stress. Under such conditions, the respiratory system may approach a physiological limit, causing further increases over time to become less pronounced. This phenomenon may occur when substrates become limiting, membrane integrity begins to deteriorate, or enzyme systems become less efficient under prolonged exposure to high temperatures.

This interpretation is consistent with the concept that high temperatures do not always produce a proportional increase in respiration over time. While moderate temperature elevation can stimulate metabolism, excessive or prolonged heat exposure may induce stress responses that alter normal respiratory regulation. High temperatures can affect enzyme stability, membrane permeability, mitochondrial function, and cellular redox balance. These changes may reduce metabolic efficiency even when overall respiration remains elevated. Thus, the lower slope at 30°C does not indicate reduced respiration but rather suggests that the fruit may have entered a different physiological state under high-temperature storage. Previous studies have also shown that thermal stress can modify respiration dynamics and reduce the proportional metabolic response in fruit tissues (Jalali et al., 2017; Joseph et al., 2021; Keshri et al., 2021; Qu et al., 2022).

The strong positive linear relationship between storage temperature and respiration rate, with an R^2 value of 0.9984, indicates that temperature explained most of the observed variation in respiration within the tested range. This result supports the conclusion that storage temperature was a dominant factor affecting respiration in namnam fruit. However, the very high linearity should not be overgeneralized. In biological systems, respiration responses to temperature are commonly nonlinear, particularly when a wider temperature range is evaluated. Over broad temperature intervals, respiration often follows an exponential or Arrhenius-type relationship because biochemical reaction rates increase in a temperature-dependent manner (Adhamatika et al., 2024; Thewes et al., 2023). Therefore, the linear pattern obtained in this study most likely reflects the limited number of temperature treatments, namely 10°C, 20°C, and 30°C, rather than a universal physiological response of namnam fruit.

The Q_{10} values provide further evidence regarding the temperature sensitivity of namnam respiration. The Q_{10} value of 1.68 for the 10–20°C interval indicates that respiration increased by approximately 1.68-fold for every 10°C increase within this range. Meanwhile, the lower Q_{10} value of 1.45 for the 20–30°C interval indicates that the proportional increase in respiration became smaller at higher temperatures. These values are lower than the commonly reported Q_{10} range of 2–3 for many fresh horticultural products (Lin et al., 2026; Niponsak et al., 2020; Saltveit, 2019). This suggests that namnam fruit exhibited moderate temperature sensitivity under the conditions of this study.

The decline in Q_{10} at the higher temperature interval is particularly important. It suggests that the effect of temperature on respiration was not constant across the tested range. At lower temperatures, an increase from 10°C to 20°C may have stimulated respiration more effectively because enzymes and cellular processes were still operating within a favorable physiological range. However, at 30°C, the fruit may have approached a condition in which respiration was already elevated, and further proportional increases were constrained. This may be related to substrate limitation, enzyme saturation, thermal stress, or changes in membrane function. In practical terms, this means that although storage at 30°C resulted in the highest respiration rate, the relative sensitivity of respiration to temperature increase was lower than that observed between 10°C and 20°C.

Compared with climacteric fruits such as mango and banana, which often show stronger temperature responsiveness during ripening, namnam fruit appeared to exhibit a more moderate respiratory response. This may indicate that namnam has distinct postharvest physiological characteristics. However, because namnam is still an underutilized fruit with limited postharvest data, further investigation is required before drawing firm conclusions. Additional temperature levels, different maturity stages, and simultaneous ethylene measurements would provide a more comprehensive understanding of its respiratory behavior.

The Arrhenius analysis showed an apparent activation energy of approximately 27.3 kJ mol^{-1}. This value indicates that the respiration process of namnam fruit was influenced by temperature-dependent biochemical reactions. Activation energy reflects the degree of temperature dependence of a reaction or process. In the context of fruit respiration, higher activation energy generally indicates greater sensitivity to temperature changes. The obtained value suggests that respiration in namnam fruit required moderate activation energy, which is consistent with the moderate Q_{10} values observed in this study.

However, the Arrhenius model showed only a moderate fit, with an R^2 value of 0.6682. This indicates that temperature explained part, but not all, of the variation in the respiration-derived rate constant. This result is reasonable because fruit respiration is not a single elementary chemical reaction. Instead, it is a complex physiological process involving multiple pathways, including substrate mobilization, enzymatic oxidation, mitochondrial respiration, gas diffusion, and stress-related metabolism. Each of these processes may respond differently to temperature. In addition, biological variation among fruits, maturity differences, tissue structure, water status, and gas exchange limitations may also contribute to deviations from ideal Arrhenius behavior.

Therefore, the activation energy obtained in this study should be interpreted as an apparent kinetic parameter rather than a fixed intrinsic constant. In this context, the Arrhenius model functions as a semi-empirical approach to describe the overall temperature dependence of respiration under the tested experimental conditions. Its predictive application beyond the tested range should be performed cautiously, particularly because only three temperature levels were used and the model fit was moderate. Additional data points would improve the reliability of the Arrhenius estimation and enable a more accurate evaluation of whether respiration follows a true exponential temperature response.

The preliminary shelf-life estimation showed that the estimated storage life decreased as storage temperature increased. This trend is consistent with the respiration data, in which higher temperatures increased CO_2 production and indicated faster metabolic deterioration. At 10°C, the estimated shelf life reached 13.46 days, suggesting that low-temperature storage was able to slow respiration-associated quality degradation. At 20°C, the estimated shelf life decreased to 9.06 days, while at 30°C, it further decreased to 6.26 days. These results indicate that each increase in storage temperature shortened the potential storage period of namnam fruit.

The physiological explanation for this pattern is that increased respiration accelerates the consumption of respiratory substrates and promotes senescence-related changes. As respiration increases, cellular reserves are depleted more rapidly, while metabolic by-products may accumulate. Higher temperatures may also accelerate other deterioration mechanisms, such as water loss, tissue softening, discoloration, microbial growth, and the development of off-flavor compounds. Although these parameters were not directly included in the model, they are commonly associated with faster quality loss in fresh fruits stored at higher temperatures. Thus,

the shelf-life estimation is consistent with the expected physiological effects of temperature on postharvest deterioration.

Nevertheless, the shelf-life values obtained in this study should be interpreted as preliminary metabolic indicators rather than definitive commercial shelf-life limits. The model was based on respiration-derived deterioration constants and applied a zero-order quality degradation assumption. This approach is useful for obtaining an initial quantitative estimate, but it does not fully represent the complexity of fruit quality deterioration. Commercial shelf life is usually determined not only by respiration but also by sensory acceptability, firmness, weight loss, visual appearance, microbial safety, and consumer preference. Because these quality thresholds were not directly measured or validated in this study, the estimated values of 13.46, 9.06, and 6.26 days should be considered respiration-based storage potential under the tested conditions.

The use of a zero-order model also requires careful interpretation. Zero-order kinetics assumes that the rate of quality decline remains constant over time and is independent of the remaining quality level. This assumption may be appropriate for certain quality indices within a limited storage period; however, fruit deterioration often involves nonlinear changes. For example, softening, microbial spoilage, or aroma changes may accelerate after a certain physiological threshold is reached. Therefore, future studies should compare zero-order and first-order models or integrate multiple quality parameters to develop a more robust shelf-life prediction model.

In summary, these findings collectively establish that storage temperature is the dominant factor controlling respiration in namnam fruit, while physiological constraints, substrate availability, and tissue-level factors introduce additional variability not captured by temperature-based models alone. Several limitations of this study should be acknowledged. First, only three storage temperatures were tested, which restricts the generalizability of the Arrhenius model and limits the detection of nonlinear respiration patterns. Second, the shelf-life estimates were derived solely from respiration data using a zero-order model, without validation against direct quality parameters such as firmness, weight loss, color, or sensory acceptability. Third, ethylene production was not measured, preventing a definitive classification of namnam fruit as climacteric or non-climacteric. Fourth, biological variation among fruits, including differences in maturity stage and tissue composition, may have contributed to the moderate Arrhenius model fit. These limitations underscore the preliminary nature of the findings and highlight the need for more comprehensive postharvest studies.

CONCLUSION

This study provides the first systematic characterization of temperature-dependent respiration kinetics in namnam fruit (*Cynometra cauliflora*), an underutilized tropical species for which postharvest physiological data were previously unavailable. Three principal conclusions can be drawn in relation to the research objectives. First, the respiration rate increased consistently with storage temperature, confirming that temperature is a primary driver of postharvest metabolic activity in namnam fruit. Second, Arrhenius analysis (Ea = 27.3 kJ mol^{-1}) and Q_{10} values (1.45–1.68) indicated moderate temperature sensitivity, with a declining respiratory response at higher temperatures suggesting the presence of physiological constraints beyond thermal acceleration. Third, the zero-order respiration-derived model estimated shelf life at 13.46, 9.06, and 6.26 days at 10, 20, and 30°C, respectively, confirming that low-temperature storage can effectively delay metabolic deterioration. These results contribute baseline quantitative data to the postharvest literature on underutilized tropical fruits and demonstrate the applicability of respiration-based kinetic modeling for preliminary shelf-life estimation. Future research should incorporate direct quality measurements (firmness, weight loss, color, soluble solids, and acidity), ethylene production analysis, sensory evaluation, and microbial assessment to validate and refine the shelf-life prediction model. Additionally, evaluations at additional storage temperatures and maturity stages are recommended to improve the robustness of Q_{10} and Arrhenius parameter estimates and to enable reliable commercial shelf-life prediction for namnam fruit.

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AUTHOR CONTRIBUTION STATEMENT

A.B. conceived and designed the research framework and supervised the overall study. F.C.K. and E.K. conducted the experimental work, including sample preparation, respiration measurements, and data collection. S.B. performed data analysis, modeling (Arrhenius and Q_{10}), and statistical interpretation. All authors contributed to manuscript writing, critical revision, and approved the final version of the article for publication.

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