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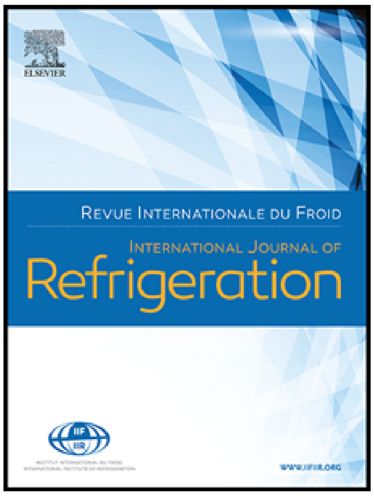

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Influence of long-distance air transport conditions on horticultural product quality: Case study of fresh mango shipment from Thailand to France

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Highlights:

- Measured data of in-flight conditions revealed the decreasing trend of air and fruit temperatures.
- Difference in mass loss of mangoes transported via direct and indirect flights was obviously detected.
- Kinetic models could predict product temperature, mass loss and peel color change as a function of a supply chain scenario.
- Stable ambient temperature and relative humidity are key factors determining the preservation of product quality.

Abstract

Four instrumented boxes of mangoes *Mangifera indica* L. cv. "Nam Dok Mai" were shipped from Bangkok, Thailand, to Paris, France, without control of the boxes' positions on the aircraft. Two boxes were shipped via a direct flight and two boxes were shipped via an indirect flight. For each box, the internal air temperature, the external air temperature and relative humidity and surface temperature of two fruits were recorded throughout the supply chain from a packing house in Thailand to a storage room in France. A maximum fruit temperature of 33 °C (during transport from an orchard to the packing house) and a minimum fruit temperature of 8 °C (in a cold room of the logistics company following arrival at the airport in France via the indirect flight) were observed. The slight temperature difference between the air and the fruit surface temperature (< 1 °C on average) for both direct and indirect flights suggests that the air was stagnant inside the box and, thus conduction was the main heat transfer mode. Models of product temperature, mass loss, and peel color changes throughout the supply chain were developed. The numerical and the experimental values were in good agreement. These models were able to predict the product mass loss and peel color evolution as a function of a supply chain scenario.

Keywords: air transport; temperature; tropical fruit; mass loss; color

Nomenclature

A	Product surface area (m^2)
b^*	Peel yellowness value (-)
C_w	Water vapor concentration in the mango peel (kg water·m^{-3} humid air)
$C_{w,\infty}$	Water vapor concentration in air (kg water·m^{-3} humid air)
E_a	Activation energy = 87,600 J·mol^{-1}
k_{ref}	Constant rate at reference temperature (d^{-1})
k_{ta}	Moisture transfer coefficient between the product and the air (m·s^{-1})
m	Product mass (kg)
m_w	Water loss due to transpiration (kg)
M_{H_2O}	Water molecular weight = 18 kg·mol^{-1}
P_{sat}	Saturated vapor pressure (Pa)
R	Gas constant = 8.314 J·mol^{-1}·K^{-1}
RH	Relative humidity of air (%RH)
t	Time (h)
Δt^*	Dimensionless time shift factor
T	Temperature (°C)
τ_T	Characteristic time of temperature evolution (h)
τ'	Characteristic time of color evolution (h)
Subscript	
a	air
0	initial
p	product
t	time
w	water

1. Introduction

Temperature and relative humidity are the key factors that determine the preservation of quality and shelf life of mangoes (*Mangifera indica* L., (Yasunaga et al., 2018)). Mango is a time-and-temperature sensitive fruit with an optimal storage temperature of 13 °C (Kader, 2008) and an optimal relative humidity of 85-95 %RH (Hussen, 2021). To maintain the product quality, mangoes should be properly handled during harvest, preparation, packing and transportation throughout the entire chain (Sivakumar et al., 2011).

The main quality attributes of mango are peel color, firmness, sugar content, mass and visual quality (Penchaiya et al., 2020). Yasunaga et al. (2018) investigated the effect of storage temperature and relative humidity on quality changes in fresh mango (*Mangifera indica* L. cv. “Nam Dok Mai”) shipped from Thailand to Japan by marine transport. The ambient temperature and relative humidity were recorded throughout the supply chain over the 18-day shipment period. The authors reported that non-refrigerated (~25 °C) transport conditions and the duration of transport between the farm and the packing house exerted a significant impact on product quality. In other words, fruit should be cooled down and stored at an appropriate temperature as soon as possible after harvest. Numerous experimental studies on mango quality can be found in the literature, but a few modeling studies have been conducted. Fukuda et al. (2014) modeled the relationship between the peel color and some quality attributes (firmness, total soluble solids - TSS, and ascorbic acid) of mangoes (cv. “Nam Dok Mai” and “Irwin”) using an artificial intelligence approach (random forests). Penchaiya et al. (2020) carried out a laboratory study and proposed first-order exponential models to predict the color and firmness evolution of mango (cv. “Nam Dok Mai”) as a function of time during constant storage temperature, and a first-order logistics model for variations in the storage temperature. Schouten et al. (2018) have developed a kinetic model to predict the mangoes softening (cv. ‘Keitt’ and ‘Kent’), which depends on the ethylene releasing rate. This rate is related to the storage temperature according to the Arrhenius’ law.

For years, the air cargo industry has played an important role in global food trade. As distribution by air typically costs 12-16 times more than marine transport (The World Bank, 2009), the key drivers for utilizing air transport are the short product shelf life and high product value (Pelletier et al., 2018). The short duration of air transport in comparison with marine transport allows minimization of product loss throughout the supply chain. For most air shipments, the time spent in flight corresponds to approximately 50 % of the total travel time, including storage and transfers at airports (Sharp, 1998). Maintaining suitable temperatures during air transport operations is challenging since the cargo may spend a long period on the tarmac. Variation of the ambient temperature due to the logistic at the airport has a significant impact on product temperature fluctuations (Thompson, 2004). Many authors revealed that high temperature variation was influenced by solar radiation (Pelletier et al., 2018), material used to manufacture the walls of the container (Heap, 2006; Oskam et al., 1998; Villeneuve et al., 2000), and airflow pattern depending on the ventilation system during the flight (Emond et al., 1999).

In spite of the temperature control issues, few studies on in-flight environmental conditions and their impacts on fresh fruit and vegetables have been undertaken. Such studies are essential in order to develop new handling methods that preserve product quality throughout a supply chain. Pelletier (2010) conducted a thermal analysis on horticultural products in an individual box placed in an aircraft container (loaded with several boxes) exposed to detrimental temperatures in the laboratory. In this study, different fruit sizes and packing arrangements were tested, and it was observed that there were small temperature differences between the pulp and air temperatures within the individual boxes (~1.5 °C) and relatively fast rates of temperature change were observed even in the core region of the boxes i.e. the temperature increased from 3 °C to 12 °C within 7 h. For the aircraft container, similar thermal behavior was observed in the fruit near the external environment, particularly in the case of the boxes located in the top row.

In Thailand, high-quality mango (*Mangifera indica* L. cv. "Nam Dok Mai") is one of major fruits exports. The export value of fresh mango increased about 6 folds in a decade from 500 million Thai Baht in 2011 to almost 3,000 million Thai Baht in 2021 (Thai Information and Communication Technology Center, 2021). This figure reflects the great demand of Thai mango from international markets. However, around 15-50% of this mango cultivar harvested are lost during transportation (Sardsud et al., 2003). To ensure fresh mango quality and minimize loss throughout the air transport supply chain, this study was conducted with the following objectives:

(i) To carry out a preliminary study to highlight the time-temperature and fruit quality evolution throughout the supply chain from postharvest of mangoes in Thailand to France including direct and indirect flights.

(ii) To develop kinetic models to predict product mass loss and color evolution as a function of temperature.

(iii) To study numerically the influence of supply chain scenarios on product quality.

As a first approach, a simple configuration was studied in this work. It involved the placing of mangoes in corrugated boxes under blind conditions during air shipment, i.e. no control of the box position in the aircraft hold which was not temperature-controlled.

2. Materials and methods

2.1 Mango characteristics

The mango investigated was *Mangifera indica* L. cv. "Nam Dok Mai". Based on measurements of 20 mangoes, the average mass was 0.415 ± 0.037 kg, the volume was $4.02\times10^{-4} \pm 3.75\times10^{-5}$ m^3, the surface area was $2.60\times10^{-2} \pm 1.28\times10^{-3}$ m^2, and the density was 1030 ± 19 kg·m^{-3}. Other thermal properties of mangoes (cultivar not specified) were assumed from ASHRAE (2018) as a moisture content of 81.71 %, a thermal conductivity of 0.418 W·m^{-1}·K^{-1}, a specific heat capacity of 3740 J·kg^{-1}·K^{-1} (above freezing), and a heat of respiration of 356.0 mW·kg^{-1} at 25 °C.

2.2 Supply chain

This study was carried out in March 2022. Mangoes were harvested 90-93 days after anthesis (80-85 % maturity) from an orchard in Chachoengsao province (13.606977 °N, 101.298767 °E), then transported to a packing house in Nakhon Pathom province (13.80253 °N, 100.06714 °E) by a noncontrolled temperature truck (157 km, 2.5 h travel duration from the orchard). At the packinghouse, the fruit were sorted and graded according to the Thai Agriculture Standard for exported fresh mangoes (MOAC, 2015), which judged its weight (> 350 g in this study) and external appearance i.e., absence of defects. To control fruit flies, the fruits were immersed in hot water until their core temperature reached 46 °C, then were held at this temperature for 10 min (total duration of 1 h). They were dried under room temperature conditions using industrial fans before being wrapped in foam net (made of polystyrene) to minimize product damage by vibration. Twelve fruits were arranged in a corrugated box (**Fig. 1**) with 4 vent holes covered by net for insect prevention, corresponding to 21 % of occupied volume. In a box, 8 recorders (iButton®, precision ±0.2 °C after calibration, ±5 %RH according to the manufacturer) were installed: 4 recorders near the side walls for internal air temperature monitoring (denoted "Ai" in **Fig. 1b**), 2 recorders in front of the vent holes for external air and relative humidity monitoring ("Ae", **Fig. 1b**) and 2 recorders inserted under the foam net, sensors facing the product, and stick on the mango peel for the product surface temperature monitoring ("M", **Fig. 1c**). These temperatures were recorded every 5 min along the supply chain from Bangkok, Thailand to Paris, France.

To ensure the repeatability, four instrumented boxes of mangoes were transported from the packing house to the airport cargo terminal for customs control, transfer to aircraft, loading and lift-off. Two boxes were sent by a direct flight and the other two boxes by an indirect flight on the same day. **Tables 1** and **2** present the time schedule of these 2 supply chains.

To highlight the influence of air transport conditions, two boxes of the same batch of mangoes were transported to the Department of Food Engineering, School of Engineering, King Mongkut's Institute of Technology Ladkrabang (KMITL), Thailand. These boxes were stored in a temperature-controlled room (average temperature 20.5 ± 0.6 °C and relative humidity 68 ± 5.0 %RH) for a duration of 11 days.

Fig. 2a shows the upstream stages of the studied supply chain in Thailand from harvest to Suvarnabhumi Airport in Bangkok (BKK). **Fig. 2b** shows the consecutive stages of the supply chain of the direct flight and **Fig. 2c** shows those of the indirect flight to Charles de Gaulle Airport (CDG) in Paris. After arrival in Paris, all boxes were received by a logistics company for delivery to the FRISE laboratory, National Research Institute for Agriculture, Food and Environment (INRAE) located in Antony, a suburb of Paris.

2.3 Quality assessment

Individual mangoes to be shipped to France were weighed and labelled before packing in the boxes while the temperature recorders were triggered to start the acquisition. This moment was considered as the initial time and the initial mass for the mangoes from both flights. As it was too complicated to conduct color measurement at the packing house, the initial color value of all mangoes shipped to France was considered to be the same value as those measured at the laboratory in Thailand for 20 °C storage treatment. This consideration could be justified because of the same fruit batch. These two quality attributes were successively measured at different time points during 20 °C storage at INRAE for both direct and indirect flights: day 3 (the first evaluation day in France), day 7, day 9, day 11 and day 14. The measurement was ended after day 14 because the mangoes were visually too deteriorated and considered as having reached the end of their saleable lifetime. Several quality attributes were assessed: mass loss, peel color, pH, TSS, firmness and visual quality based on score ranging (peel color, shrivelling, chilling injury, and decay). Almost the same quality attributes were measured for the mangoes stored in the laboratory in Thailand.

To avoid data redundancy, only the product mass loss and peel color evolution are presented in this article since they are considered as the main criteria of product saleability.

2.3.1 Mass loss

The product mass loss is related to water evaporation from the surface which leads to product shrinkage and texture modification.

Nine mangoes from each supply chain (direct and indirect flights) were randomly selected and weighed at different time points (0, 3, 7, 9, 11 and 14 days) using a digital balance (Sartorius CPA34001P, accuracy 0.1 g). Referencing the initial mass of the fruit (m_0) measured in the packing house in Thailand and the mass on different days (m_t) at INRAE in France, the % mass loss was calculated using **Eq. (1)**:

$$Mass\ loss\ (\%) = \frac{m_0 - m_t}{m_0} \times 100 \quad (1)$$

2.3.2 Color

The peel color of each individual mango was assessed by a non-destructive spectroscopic method using a chroma meter because it is handy and practical. The value of $L*$, $a*$ and $b*$ were recorded by placing the sensor at 2 positions on the mango peel (1 measurement/mango side) of 9 mangoes. It is to be emphasized that $L*$ represents the product whiteness, $a*$ the product redness (positive value) and greenness (negative value), and $b*$ the product yellowness (positive value) and blueness (negative value). The $b*$ represents the product visual quality to the greatest extent.

3. Model development

3.1 Thermal model

Product temperature is considered uniform in a box and its temperature varies exponentially with the ambient temperature throughout the supply chain as expressed in **Eq. (2)**.

$$\frac{dT_{\mathrm{p}}}{dt} = \frac{\left(T_a - T_p\right)}{\tau_T} \tag{2}$$

where T_p is the predicted product temperature, T_a is the measured ambient temperature, and τ_T is the characteristic time of the temperature evolution (h) which depends on the product properties and geometry (heat capacity, mass, and surface area) and the heat transfer coefficient in the box. The τ_T value was identified by fitting the product temperature to that measured throughout the supply chain.

3.2 Mass loss model

As in other horticultural products, mango mass loss is determined by the difference in water vapour concentration between the mango peel and the surrounding air. A simple model describing the evolution of water loss (m_w) due to evaporation was used in our study (**Eq. (3)**):

$$\frac{dm_w}{dt} = k_{ta}A\left(C_w - C_{w,\infty}\right) \tag{3}$$

where k_{ta} is the moisture transfer coefficient between the product and the air (including peel resistance) ($\mathrm{m \cdot s^{-1}}$), where A is product surface area (= 2.60×10^{-2} $\mathrm{m^2}$, average of 20 mangoes), m_w is the water loss due to transpiration (kg), C_w is the water vapour concentration in the mango peel (kg water$\cdot$m^{-3} humid air). This value is related to the saturated vapour pressure at the product surface temperature $P_{sat}(T_s)$, which can be represented by **Eq. (4)**:

$$C_w = \frac{M_{H_2O}P_{sat}(T_s)a_w}{RT_s} \tag{4}$$

M_{H_2O} is the molecular weight of water (18 kg$\cdot$mol^{-1}) and R is the gas constant = 8.314 J.mol^{-1}.K^{-1}. The water activity (a_w) is considered constant and equal to 1 throughout the supply chain. $C_{w,\infty}$ is the water vapour concentration in the surrounding air (kg water$\cdot$m^{-3} humid air), and it can be calculated using **Eq. (5)**:

$$C_{w,\infty} = \frac{M_{H_2O}P_{sat}(T_a)}{RT_a} \cdot \frac{RH}{100} \tag{5}$$

The saturation pressure of water vapour ($P_{sat}(T)$ in Pa) can be determined from **Eq. (6)** (Batina and Peyrous, 2018):

$$P_{sat}(T_a) = 10^{\left(2.7877 + \frac{7.625T_a}{241.6+T_a}\right)} \tag{6}$$

The value of the moisture transfer coefficient (k_{ta}) was obtained by fitting the predicted mass loss (obtained using **Eq. (3)**) with the experimental values reported by Penchaiya (2018) for the same mango cultivar (cv. "Nam Dok Mai"). In that study, mangoes were stored under 4 different constant ambient conditions (constant temperature and relative humidity). For each storage condition, the mass loss of 30 mangoes was measured every day until day 8 and then every 2 days until day 14. The fitted k_{ta} value (3.01×10^{-4} m.s^{-1}) was then used in **Eq. (3)** to predict the product mass loss under variable conditions such as those investigated in the experimental study conducted by Penchaiya (2018) i.e., mangoes stored at a temperature and relative humidity of 13.4 °C/91.6 %RH respectively for 12 days then under 25-28 °C/75.5 %RH conditions for an additional 8 days (20 days in total). Good agreement between the predicted and experimental values (**Fig. 3**) was obtained.

After having validated the model as described previously, the temperature and relative humidity of the air and the surface temperature measured on the peel of the mango and recorded every 5 min. throughout the 14-day supply chain we investigated, then were applied to **Eq. (2)** to predict the product mass loss evolution.

3.3 Color

As mentioned in Section 2.3.2, b^* is a parameter representing the product yellowness, which is a commercial quality criterion for mango. Penchaiya et al. (2020) developed a logistic model for b^* prediction of mango (cv. "Nam Dok Mai") exposed to variable temperatures such as those in a supply chain as below:

$$b^* = b^*_{min} + \frac{b^*_{max} - b^*_{min}}{1 + exp(-\tau' + \Delta t^*)} \tag{7}$$

where b^*_{min} and b^*_{max} are the lowest and highest asymptotic values of the measured b^*, respectively. The characteristic period of time during which color evolves, τ', is defined as:

$$\tau' = \int_0^t k_{ref} e^{\frac{E_a}{R}\left(\frac{1}{Tref} - \frac{1}{T(t')}\right)} dt' \tag{8}$$

where Δt^* is a dimensionless time shift factor. Δt^* depends on the initial value of b^* (b^*_{ini}), which can be estimated using **Eq. (9)**:

$$\Delta t^* = ln\left(\frac{b^*_{max} - b^*_{min}}{b^*_{ini} - b^*_{min}} - 1\right) \tag{9}$$

In the case of the mango cv. "Nam Dok Mai" stored at temperatures ranging from 13 to 30 °C, Penchaiya et al. (2020) proposed:

b^*_{min} = 27.85, b^*_{max} = 45.78, k_{ref} = -0.468 d^{-1}, and E_a = 87,600 J·mol^{-1}.

Δt^* = 2.61 (estimated by **Eq. (9)** taking into account the measured initial value of b^*_{ini} (32.34).

It is to be emphasized that the b^* value increases with time. Where there are no experimental data, b^*_{min} and b^*_{max} values can also be estimated by an expert.

The simulation was undertaken with time intervals dt of 5 min, (being equivalent of the data acquisition during air transport).

3. Results and discussion

3.1 Experimental results

3.3.1 Air and product temperatures throughout the supply chain

Figs 4 and **5** present the air and product surface temperature evolution measured at different positions in Box 1 for direct and indirect flights, respectively.

The measured data of direct and indirect flights revealed the decreasing trend of air and fruit temperatures during the in-flight period. Considering all the steps, the maximum fruit temperature of 33 °C was observed during transport from the orchard to the packing house in Thailand, and the minimum fruit temperature of 8 °C was observed in a cold room of the logistics company following arrival at Charles de Gaulle Airport in Paris via the indirect flight. This is related to the fact that the indirect flight arrived at noon at Charles de Gaulle Airport, meaning that delivery to INRAE before the institute closing hour was not possible due to the time delay at the custom service. Thus, the shipment was delivered in the next morning before which the mangoes were kept in the cold storage overnight. In spite of this cold storage upon arrival at the airport in our case, this step is quite rare during a real commercial delivery. For the direct flight, the in-flight duration was 12 h 45 min. For the indirect flight, the in-flight duration was 1.50 h for the first flight, 6.60 h for the second flight, and 7.58 h for the third flight, while the duration of transfer was 1.50 h between the first and the second flights, and 4.07 h between the second and third flights. The total duration of the indirect flight (in-flight and transit time) was 21 h 15 min.

It should be borne in mind that the position of the boxes on the aircraft was unknown, and Emond et al. (1999) reported large spatial temperature variations on aircraft. In general, the air and surface temperatures were very close: the temperature difference between the air and the surface temperature of the mangoes was 0.5 °C on average for the direct flight and 0.7 °C on average for the indirect flight. The difference between the air and product temperatures of the two replications (Box 1 and Box 2 on the same flight) was not significant (0.5 °C on average). This led us to assume that there is low air renewal in the boxes, and thus the air was stagnant. This might be due to the fact that during air transport, the studied boxes were surrounded by other boxes or they were located in a poorly ventilated position within the aircraft. Hence, conduction is the dominant heat transfer mode inside the box. This observation is in agreement with that reported by Pelletier (2010) who conducted thermal analysis in a laboratory using a similar configuration. It needs to be noted that small differences between the air and the fruit surface temperatures could also be observed under high airflow rate conditions. However, high airflow was not our case since the boxes were closed and held in low airflow environments along the supply chains i.e., airflow rates are typically 0.02-0.06 $L\cdot kg^{-1}\cdot s^{-1}$ in transport and 0.001-0.002 $L\cdot kg^{-1}\cdot s^{-1}$ in cold storage (Wu et al., 2018). The flow rate would be even lower during air transport because of no ventilation system in the aircraft container (ULD). Moreover, the vent holes on the walls of the boxes are covered by net, which in turn resists air infiltration.

There were instances where the difference between the air and product temperatures varied by up to 5 °C during periods of rapid cooling (beginning in cold storage) and warming (beginning of non-refrigerated transport to INRAE). In the indirect supply chain (between activities 9 and 10, **Fig. 5**), the mango temperature decreased to about 8 °C, and this can be explained by the fact that the boxes were stored in a cold room used by the logistics company.

3.1.2 Product mass loss

Fig. 6 presents the percentage of product mass loss from harvest to storage in a room maintained at 20 °C for 12 days after the direct and indirect flights and that observed following storage in a laboratory test room maintained at a temperature of 20 °C. Each point represents the average value of 9 mangoes. The linear relationship with time is obtained for all conditions. The mass loss seen in the case of the laboratory test room maintained at a temperature of 20 °C is the lowest, while that observed for the indirect flight supply chain was the highest. This result can be explained by the higher amplitude of temperature fluctuations and the longer duration of air transport and transit periods. These temperature fluctuations induce relative humidity variations along the supply chain, both of them have an impact on the product mass losses. Knowledge of the mass loss threshold value for saleability of the studied mangoes (*Mangifera indica* L. cv. “Nam Dok Mai”) and the product shelf life could be determined. Taking into account this finding, the supply chain should be well-managed to ensure fruit quality up until consumption. Nunes and Emond (2007) have reported that the maximum postharvest life of mangoes (cv. 'Tommy Atkins' and 'Palmer') stored at 20 °C is 5 days.

*3.1.3 Color parameter b**

The value b^* measured at day 0 and on different days during storage following air transport is shown in **Fig. 7**, increasing until day 7 for the direct flight and day 11 for the indirect flight, then the value stabilized until day 14 for both flights. It is noteworthy that the peel color b^* value seemed to reach an asymptote following a number of days that depended on the supply chain. The differences in mango peel color for the direct and indirect supply chains could be explained by the variation in time-temperature history (or accumulated time × temperature unit) of these two chains. Moreover, this difference could be explained by the fact that for the indirect flight supply chain, the product temperature decreased and reached 8 °C during storage overnight in the cold room of the logistics company prior to delivery to INRAE. It should be borne in mind that each point is an average value of 18 measurements (one measurement on each side of 9 mangoes). The measurement of the b^* value of mangoes stored in a laboratory test room at a temperature of 20 °C in Thailand was not undertaken.

3.2 Identification of characteristic time of temperature evolution

The characteristic duration of temperature evolution τ_T was identified by fitting the predicted product temperature evolution throughout the supply chain (using **Eq. (2)**) with the measured values. The result is shown in **Table 3**.

The value of τ_T was about 1-2 h longer with the direct flight in comparison to that obtained with the indirect flight. This result means that the product was less responsive to the ambient temperature (that is, the rate of temperature change was slower) in the case of the direct flight supply chain than that of the indirect flight. This led us to suppose that the boxes may have been located at the center of a container during the direct flight, and more so on the edge of a container during the indirect flight. The τ_T value difference between the 2 boxes on the same flight could be explained by the difference in box positions within the same container (e.g., box 2 on top of box 1). These fitted τ_T values can be used to predict the product temperature evolution in different supply chain scenarios given solely ambient conditions. Virtual scenarios were developed as an illustration of the influence of the supply chain on the product quality (mass loss and color) using a modeling approach presented in **Section 3.4**.

3.3 Comparison between measured and predicted results

3.3.1 Product mass loss

A comparison between the experimental and predicted mass loss is shown in **Fig. 8**. There is good agreement between the predicted and measured values for the direct flight (RMSE = 1.4 % mass loss). However, for the indirect flight, the predicted values are slightly underestimated (RMSE = 2.9 % mass loss). The difference is observed from day 3 until the end of the experiment. This discrepancy may be explained by the uncertainty of the humidity measurement in the box due to the accuracy of the hygrometer. In fact, the temperature recorders were previously calibrated; however, the calibration of hygrometer was not possible in our study. In the storage cold room at a temperature of 20 °C, in which the temperature and the relative humidity were controlled and homogeneous, the model shows the best performance with experiments (RMSE = 0.8 % mass loss), in comparison to the field studies. It should be emphasized that the prediction of mass loss is very sensitive to the measured relative humidity, a difference of a few percent may lead to a large difference in mass loss. Hence, robust, accurate probes should be used for humidity measurements, and this is not always possible when conducting field experiments.

3.3.2. b value*

Fig. 9 shows a comparison between the measured and predicted b^* values. Good agreement was obtained. It needs to be noted that the predicted initial value of b^* were determined from **Eq. (7)** in which $b^*_{min}$and b^*_{max} were taken from the values estimated with more than hundreds of mangoes (cv. "Nam Dok Mai") by Penchaiya et al. (2020). The evolution of measured and predicted b^* values exhibited the same tendency i.e., the value increases with time and approaches a stable value after 8-10 days. The discrepancy observed at the beginning (< 3 days) could be explained by the difference of the initial b^* value. As explained previously, the high number of fruits used for the model development by Penchaiya et al. (2020) would assure the prediction precision for other fruit batches.

3.4 Influence of the supply chain scenario

Three virtual scenarios were developed for a 6-day supply chain: scenario 1 considered as a reference consists of a constant ambient temperature of 12 °C and 80 %RH, scenario 2 takes into account potential temperature abuse that can occur on airport tarmacs during departure and arrival, and scenario 3 consists of storage under non-optimal conditions following air transport (18 °C, 70 %RH) (**Fig. 10**). The ambient temperature and relative humidity evolution of these scenarios are the input parameters of the models.

The predicted % mass loss and b^* value corresponding to these 3 scenarios are presented in **Fig. 11**. As expected, it was shown that the constant conditions (scenario 1) led to less product mass loss and better preserved peel color (a lower b^* value). The rate of mass loss increased during the period of high vapour pressure deficit at the fruit surface in comparison with the surrounding air, i.e., high ambient temperature and low relative humidity. The mass loss is co-incident with the peel color change of fruit. Thus, b^* increases. In scenario 2, the quality attributes deteriorate more rapidly, but the impact of the temperature abuse and humidity changes are limited by their short duration (4 h). For scenario 3, although temperature and humidity abuse is less severe than in scenario 2, the deterioration of the fruit quality is more significant due to its longer duration. These results emphasize that both the intensity and the duration of temperature abuse are of major importance in the deterioration of products. The storage conditions used for mangoes should be optimal up until consumption in order to ensure quality and to avoid product waste.

3.5 Overall discussion

Although the present study used experimental data generated by an independent study (Penchaiya et al., 2020) to develop the model of mass loss and color evolution along the logistic chain of mango.

The main limitation of this study concerns the reproducibility and representativeness of the data because only one batch along 2 supply chains was considered. To address these limitations, the solution would be to replicate the field study as many times as possible as proposed by Derens-Bertheau et al. (2015). In that study, more than a hundred food products were instrumented and dispatched through various ground logistic chains so that the variability of the logistics chains was thoroughly represented.

The implementation of the field study presented in this paper is complicated to execute as it requires excellent logistics coordination among the professionals in different sectors (e.g., agriculture, packing house, carrier, phytosanitary control at custom service, airport logistics in Bangkok and in Paris, on-field instrumentation by KMITL, temperature analysis by INRAE and quality assessment by both institutions). For this reason, only a few measurements of air and product temperatures during international air transport were conducted and few fruit samples were used to evaluate the quality evolution.

An additional limitation of this study is the validity of the results with respects to the biological maturity and variability of the products as only one batch was studied. The presented data represents only the intra-batch fruit variability of a single batch. The presented results might be different from the products harvested at other times of the same season. To account for the likely variability, the solution would be to reproduce such experiments at different times of the season. The results of this study demonstrated the potential for quality models to be used to predict quality evolution through a complex supply chain.

4. Conclusions and perspectives

An air shipment of mangoes in instrumented corrugated boxes was studied for the first time without control of the position of the boxes aboard the aircraft. This fruit is temperature-sensitive and requires an optimal temperature of 13 °C throughout the supply chain. Four instrumented boxes of mangoes were sent from Bangkok, Thailand, to Paris, France: two boxes were shipped on a direct flight and two boxes were shipped on an indirect flight. The product quality was assessed at the packing house in Thailand and in a controlled-temperature room in France on different storage days until the end of life of 14 days. A maximum fruit temperature of 33 °C (during transport from the orchard to the packing house) and a minimum fruit temperature of 8 °C (in the cold room of the logistics company following arrival at Charles de Gaulle Airport in Paris via an indirect flight) were observed. The slight temperature difference between the air and the fruit surface (<1 °C on average) for both the direct and indirect flights led us to suppose that the air was stagnant in the box and, thus conduction was the main heat transfer mode. Models of product mass loss and peel color change throughout the supply chain were developed. The numerical and the experimental values were in good agreement. These models were able to predict the product quality evolution as a function of a supply chain scenario.

The results of this study will be used to design another field study to be conducted in 2023. This future study will consist of an aircraft container fully loaded with boxes of mangoes (about 160 boxes in total), which will allow the reproducibility of analysis data and the study of the heterogeneity of temperature distribution according to the box position. This knowledge is useful for the understanding of airflow, heat transfer phenomena and model development, which are original since few data are available in literature in comparison with land or sea transportation.

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Table 1 Direct flight schedule

Activity number	Date	Local time of Thailand	Duration between activities n and n-1	Source of data
0. Packing house	21/03/2022	12:01	0	KMITL experimenter
1. Transfer of all boxes to the storage room of the packing house	21/03/2022	15:31	3.50 h	Temperature profile from temperature recorders
2. Departure from the packing house	22/03/2022	9:00	17.50 h	Packing house manager
3. Arrival at the airport cargo terminal	22/03/2022	15:00	6.00 h	Packing house manager
4. Departure from the airport (BKK)	23/03/2022	00:05	9.08 h	Boarding pass TG930 Boeing 787
5. Arrival at Paris CDG Airport	23/03/2022	12:50	12.75 h	Boarding pass TG930 Boeing 787
6. Arrival at INRAE	23/03/2022	20:20	7.50 h	INRAE laboratory report

Table 2 Indirect flight schedule

Activity number	Date	Local time of Thailand	Duration between activities n and n-1	Source of data
0. Packing house	21/03/2022	12:01	0	KMITL experimenter
1. Transfer of all boxes to the storage room of the packing house	21/03/2022	15:31	3.50 h	Temperature profile from temperature recorders
2. Departure from the packing house	22/03/2022	9:00	17.50 h	Packing house manager
3. Arrival at the airport cargo terminal	22/03/2022	15:00	6 h	Packing house manager
4. Departure from the airport (BKK)	22/03/2022	21:10	6.17 h	Boarding pass EK0379 Boeing 777
5. Arrival at Phuket Airport (HKT)	22/03/2022	22:40	1.50 h	Boarding pass EK0379 Boeing 777
6. Departure from Phuket Airport (HKT)	23/03/2022	00:10	1.50 h	Boarding pass EK0379 Boeing 777
7. Arrival at Dubai Airport (DXB)	23/03/2022	06:46	6.60 h	Boarding pass EK0379 Boeing 777
8. Departure from Dubai Airport (DXB)	23/03/2022	10:50	4.06 h	Boarding pass EK0073 Airbus A380
9. Arrival at Paris CDG Airport	23/03/2022	18:25	7.58 h	Boarding pass EK0073 Airbus A380

10. Arrival at INRAE	24/03/2022	14:30	20.08 h	INRAE laboratory report

Table 3 Characteristic time of temperature evolution τ_T (h) of mango boxes in the supply chain from Thailand to France via direct and direct flights

Box number	Direct flight		Indirect flight	
	τ_T **(h)**	**RMSE (°C)***	τ_T **(h)**	**RMSE (°C)**
1	3.2	0.09	2.2	0.35
2	3.5	0.42	1.3	0.54

*RMSE (Root Mean Square Error) is defined as $\sqrt{\frac{\sum_{i=1}^{n}(T_{p,meas}-\hat{T}_p)^2}{n}}$ where n = number of temperature recordings, $T_{p,meas}$ = measured temperature, and $\hat{T}_p$ = predicted temperature.

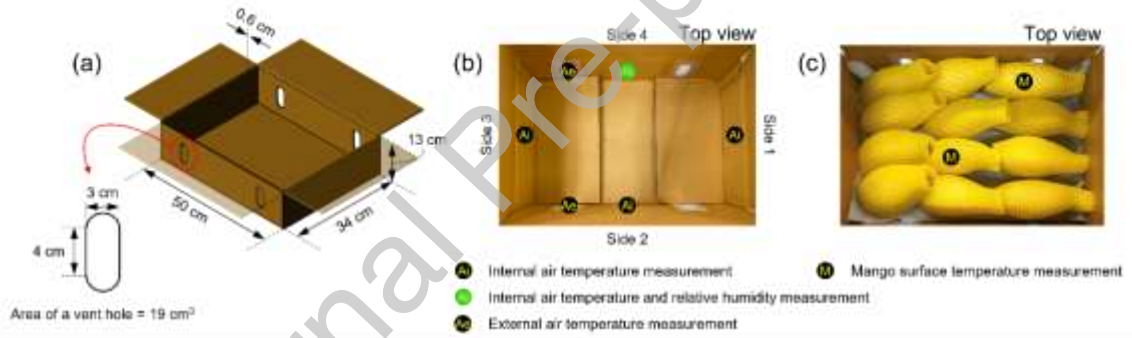

Fig. 1 Corrugated box loaded by 12 mangoes: (a) box and vent hole dimensions, (b) 6 positions of air temperature and relative humidity measurements, (c) 2 positions of product surface temperature measurement.

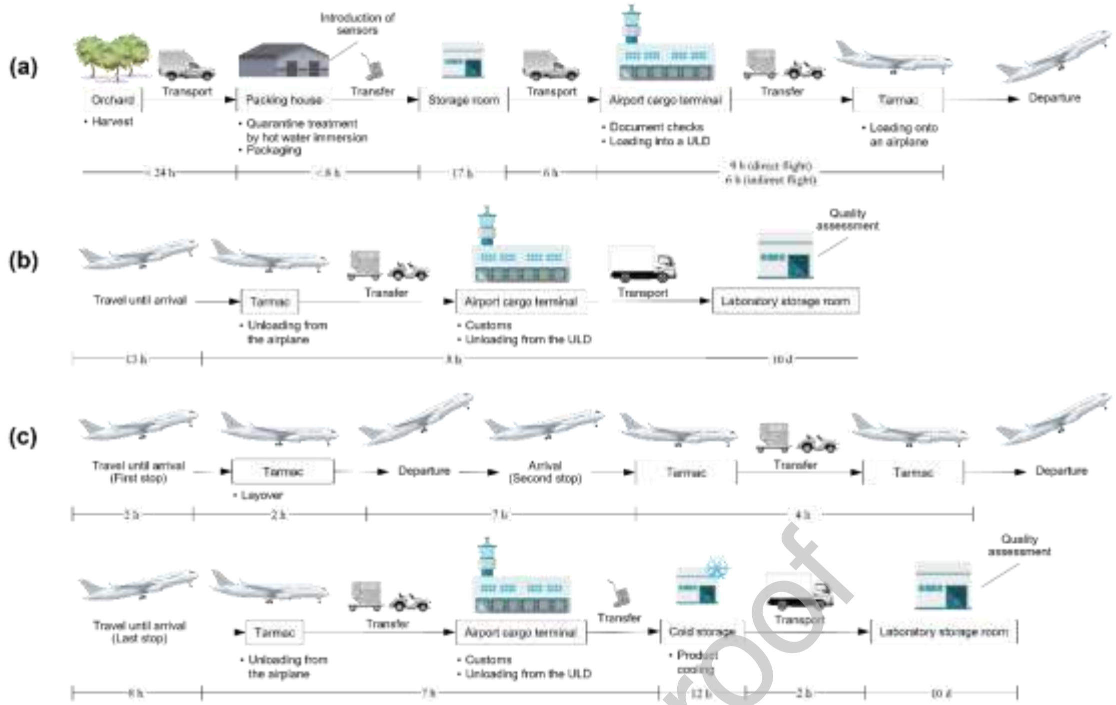

Fig. 2 Different steps of the studied supply chain: (a) upstream steps in Thailand, (b) steps of direct flight, (c) steps of indirect flight.

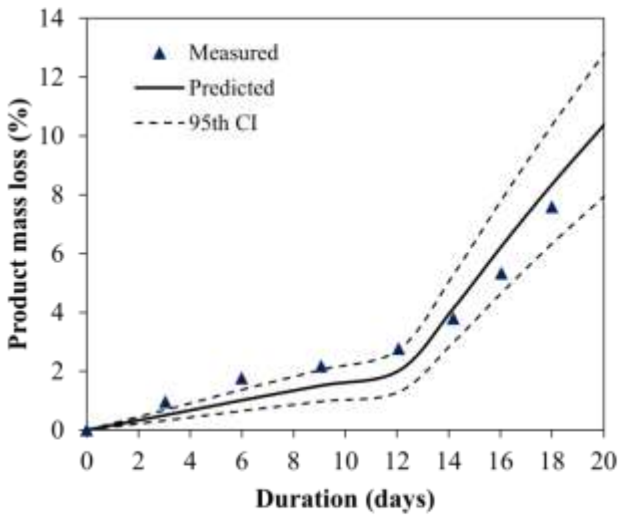

Fig. 3 Model validation by comparing the predicted product mass loss (%) with the experimental values for 2 storage conditions: 13.4 ± 0.5 °C/91.6 ± 3.0 %RH for 12 days then in 25-28 °C/75.5 ± 5.2 %RH for 8 days (experimental data from Penchaiya (2018)). CI = Confidence Interval due to uncertainty of humidity measurement.

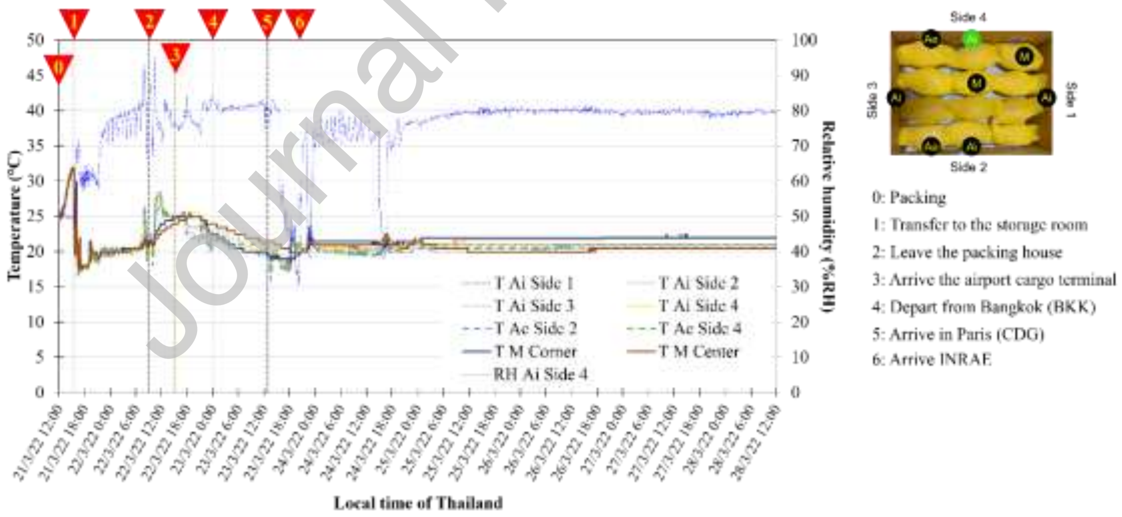

Fig. 4 Time-temperature profile in Box 1 direct flight with activity numbers.

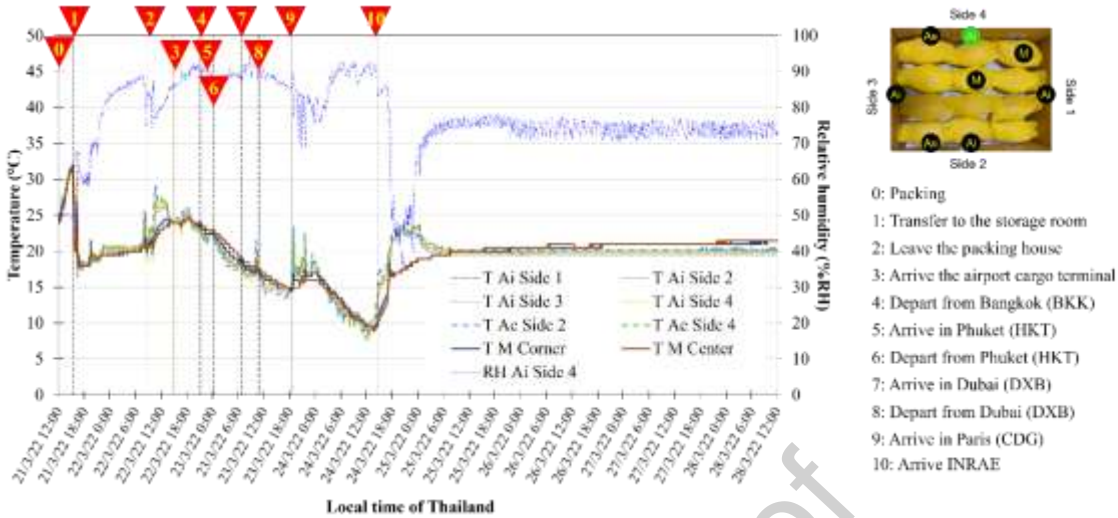

Fig. 5 Time-temperature profile in Box 1 indirect flight with activity numbers.

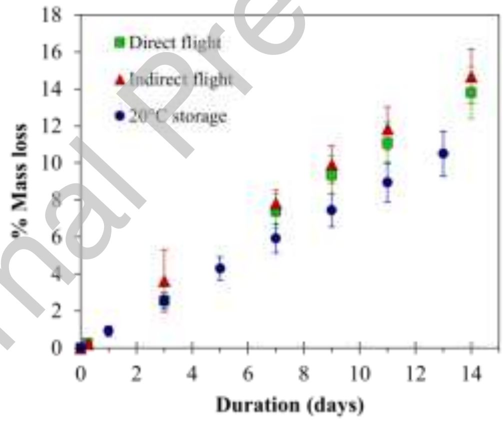

Fig. 6 Experimental mass loss variation (%) during storage for several days after 2 supply chain scenarios (direct and indirect flights) in comparison to the one stored in a 20 °C laboratory test room. Error bars represent the standard deviation of 9 samples.

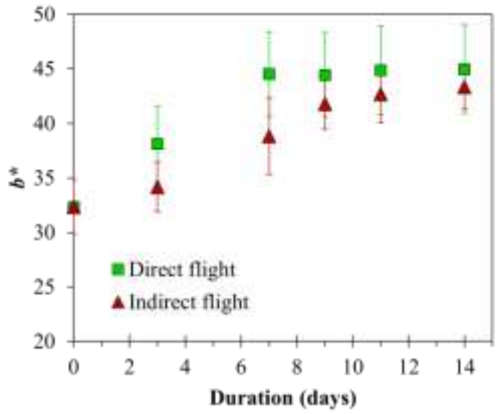

Fig. 7 Experimental values of color parameter b^* variation with storage time for 2 supply chain scenarios including direct and indirect flights. Error bars represent the standard deviation of 9 samples.

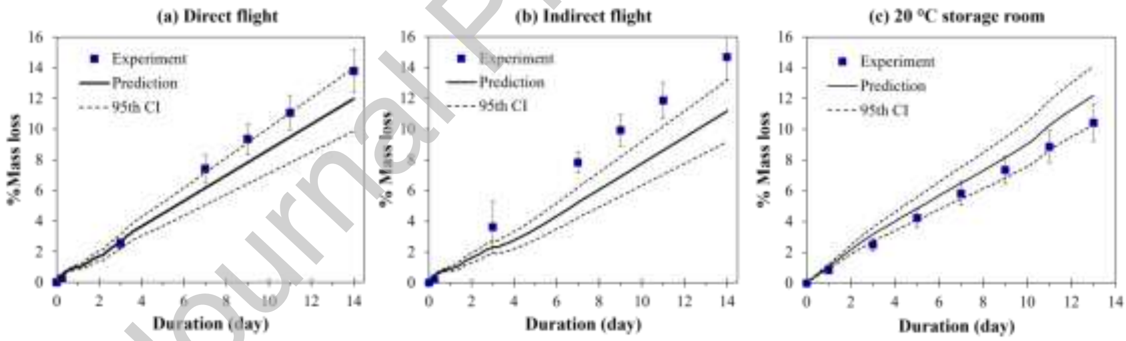

Fig. 8 Comparison between measured and predicted values of mass loss during storage for (a) supply chain with direct flight, (b) supply chain with indirect flight, and (c) storage in 20 °C room. CI = Confidence Interval due to uncertainty of humidity measurement.

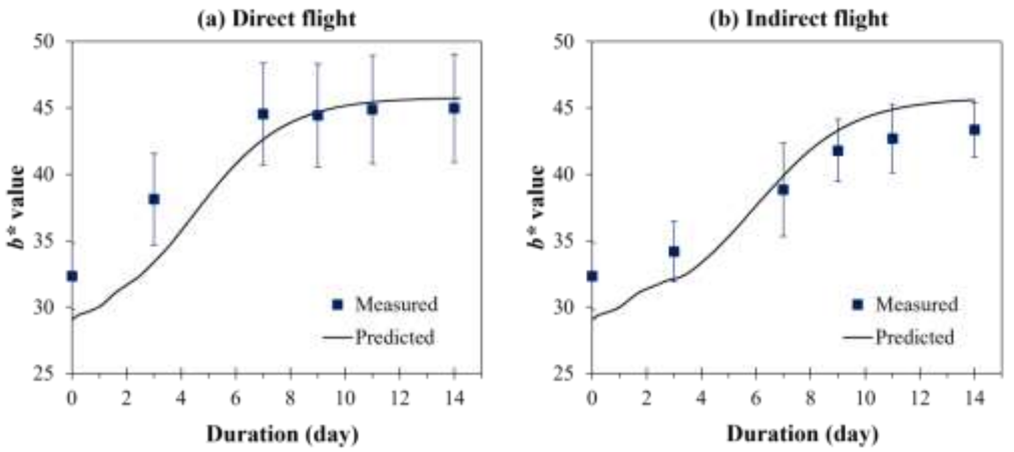

Fig. 9 Comparison between measured and predicted values of color parameter b^* variation with storage time (a) supply chain with direct flight and (b) supply chain with indirect flight.

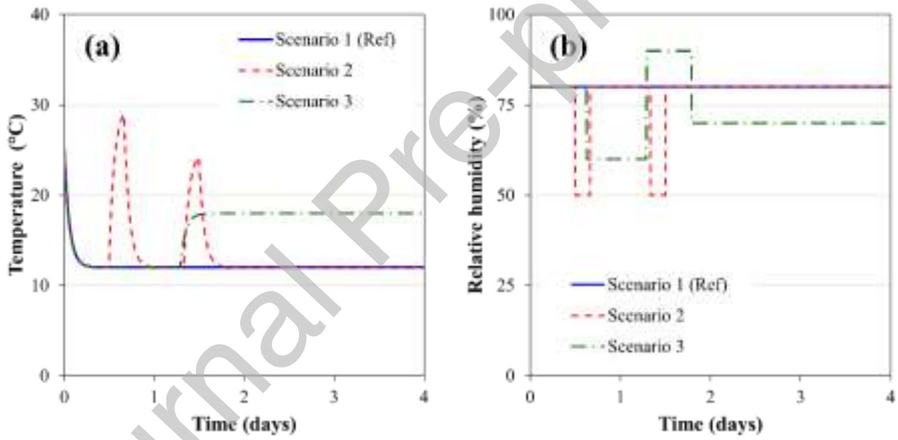

Fig. 10 Three virtual supply chain scenarios: (a) evolution of ambient temperature and (b) evolution of relative humidity. Note: scenario 1 (blue line) is a reference scenario (constant temperature of 12 °C and constant relative humidity of 80%), scenario 2 (red dash line) represents temperature break in airport tarmacs, scenario 3 (green dash-dot line) represents high ambient temperature and low relative humidity in storage room after air transport.

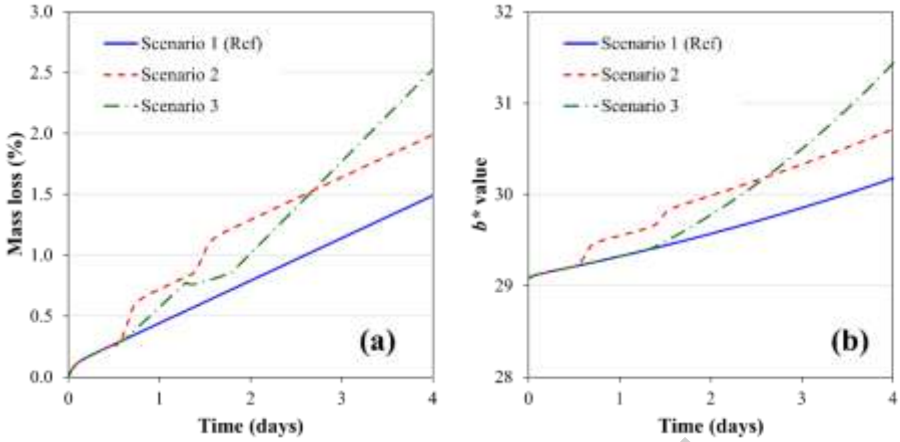

Fig. 11: Predicted evolution of product quality according to 3 virtual supply chain scenarios (a) product mass loss and (b) color (b^* value).

Declaration of Interest Statement

Please check the following as appropriate:

☑ All authors have participated in (a) conception and design, or analysis and interpretation of the data; (b) drafting the article or revising it critically for important intellectual content; and (c) approval of the final version.

☑ This manuscript has not been submitted to, nor is under review at, another journal or other publishing venue.

☑ The authors have no affiliation with any organization with a direct or indirect financial interest in the subject matter discussed in the manuscript

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