Experimental simulation of temperature non-uniformity in a loaded container along air cargo supply chain: Mango case study

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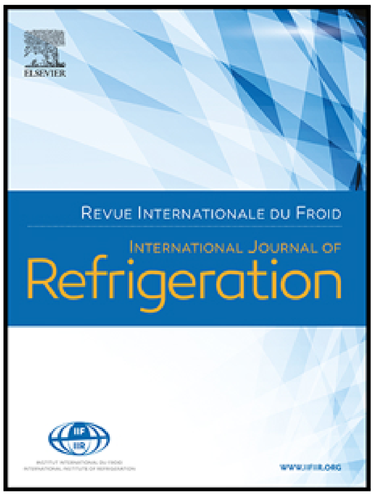

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Experimental study of air cargo temperature variations and its impact on mango quality

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Title and Keywords in French

Title

Experimental study of air cargo temperature variations and its impact on mango quality

Étude expérimentale des variations de température du fret aérien et de leur impact sur la qualité des mangues.

Keywords: air transport; export supply chain; temperature; tropical fruit; mass loss

Mots-clés : transport aérien ; chaîne d'approvisionnement à l'exportation ; température ; fruit tropical ; perte de masse.

Highlights

- Fruit temperatures across the supply chain varied between 16°C and 31°C.
- Temperature variations of fruits in upper and base cartons differed during cruising.
- Carton positions in the ULD container showed no impact on product quality.
- Superior product quality was obtained during storage at 16 °C compared to 21 °C.
- Estimation of product mass loss using model based on temperature and humidity history.

Abstract

An air cargo supply chain for fresh mango was investigated from Thailand to France. Measurements of air temperature, air relative humidity, and fruit (peel) temperature were conducted using thermo-hygrometer data loggers in cartons. In a Unit Load Device (ULD) containing 148 cartons, twenty-seven instrumented cartons were placed at different positions to observe spatial and temporal temperature variations during 12 h cruising. At the destination, mango quality attributes were assessed at different time-points during 15-day storage at 16.1 °C and 21.6 °C. Throughout the supply chain, fruit temperatures ranged from 16.6 °C to 30.5 °C. During cruising, fruit temperatures in upper cartons remained almost constant, whereas base carton temperatures continuously decreased from 26.1 °C to 18.1 °C. Because of a short cruising period in comparison to a storage duration at the destination and proper ambient temperature condition during the experiment, carton position in the ULD had no discernible impact on fruit quality during storage. Fruit stored at 16.1 °C preserved superior fruit quality compared to 21.6 °C storage. For the same storage temperature, better quality of fruits stored in Thailand demonstrated the impact of air shipment on product degradation. The measured temperature and relative humidity evolutions were used as input parameters of a mass loss evolution model. A comparison with the measured data exhibited good agreement (RMSE < 1.8% mass loss). Considering 10% mass loss as a critical value, this model allows an estimation of the product shelf life based on a supply chain scenario.

Keywords: air transport; export supply chain; temperature; tropical fruit; mass loss

Nomenclature

a^*	color value a^* (green to red)
A	product surface (m²)
b^*	color value b^* (blue to yellow)
C_w	water vapor concentration (kg of water vapor per m^3 of humid air, $kg_v \cdot m_{ha}^{-3}$)
k_{ta}	water transfer coefficient between the product and the air ($m \cdot s^{-1}$)
L^*	color value L^* (black to white)
m	mass (kg)
ML	mass loss (%)
P_{atm}	atmospheric pressure (Pa)
$RMSE$	root-mean-square error
t	time
T	temperature
ω_a	humidity ratio (kg of water vapor per kg of dry air, $kg_v \cdot kg_{da}^{-1}$)
$\omega_{a,sat}$	humidity ratio of saturated air ($kg_v \cdot kg_{da}^{-1}$)
YI	yellow index

1. Introduction

The global demand for fresh fruits and vegetables is increasing due to consumer shift towards healthy diets (Yousuf et al., 2020). Since some of the fruits and vegetables are highly perishable and sensitive to time and temperature/humidity, air transport is required to transport products over long distance and ensure product quality at delivery. However, the International Air Transport Association (IATA) data indicate that 20% of perishable products shipped by air are damaged, mostly because of temperature excursions during handling by airlines or airports. (Buxbaum, 2018).

In practice, most of the ground operations (customs procedures, cargo cold rooms and delivering on board), are performed at ambient temperatures leading to variations of ambient and product temperatures (Mercier et al., 2017; Thompson, 2004). These grounding operation may typically last for at least 6 hours before departure time (Dimerco, 2021). On the tarmac, the temperature in containers may decrease or increase to –50 °C and 50 °C in winter and summer, respectively (Nunes et al., 2006; Pelletier et al., 2018). In addition, several studies showed temperature variations during loading, cruising, and unloading that may differ from the recommended storage temperatures (Abad et al., 2009; Mai et al., 2012; Pelletier et al., 2005; Singh et al., 2009; Villeneuve et al., 2000). For example, Émond et al. (1999) measured the air temperatures inside the cargo holds of Boeing 747-400 combi during 6-h flight and observed that the temperatures varied in the range of 10-32 °C depending on the location of the cargo in the aircraft (forward hold, aft hold, and main deck). The authors suggested that the forward hold showed good conditions for the transport of perishable products. In addition to temperature variations, fruits and vegetables may reach very high temperature upon arrival at their final destination due to accumulated heat of respiration inside the aircraft containers (Laurin et al., 2003).

In the literature, data on relative humidity in aircraft's cargo holds are scarce. A review by Nagda and Hodgson (2001) shows that the average humidity levels in the aircraft cabins ranged from 14%RH to 19%RH. The same level of relative humidity is expected in the lower deck of the aircraft as it is a part of the same air conditioning system (Laurin et al., 2006). The low relative humidity in the aircraft's cabin is mainly attributed to pressurization at high altitudes (71-75 kPa) (Laurin et al., 2006; Singh et al., 2009). In a recent study based on the investigation of 46 flights, a wider range of humidity levels of 10%RH to 40%RH were reported (Lou et al., 2022).

Temperature and humidity fluctuations during the supply chain may lead to water condensation and evaporation on product surface, which could result in quality degradation. Laurin et al. (2003) evaluated at lab-scale the impacts of temperature fluctuations (1 °C, 10 °C, and 20 °C) during simulated air shipment on the quality of asparagus cv. *Lucullus* (weight loss, visual quality, firmness, and fiber content). The authors observed a significant influence of temperature during air-shipment on asparagus shelf-life and suggested use of forced-air cooling just after air shipment for extending shelf life by 7 days. Srisawat et al. (2022) found that the mango (cv. 'Nam Dok Mai Si Thong') under simulated supply chains with a short exposure to ambient temperature (40 ± 2 °C) and solar radiation for 2 hours had shelf life 2 days less than the case without. Several studies have shown that temperature and relative humidity are the key factors affecting the quality and shelf life of fruits and vegetables (Brasil and Siddiqui, 2018). However, they are often undertaken under well-controlled laboratory conditions. The field study with real products is rare due to the cost and complexity of implementation. Therefore, product models were used instead of real products for field study such as water bottles (Pelletier et al., 2018) and empty boxes (Singh et al., 2009). Few studies on real in-flight environmental conditions and their impacts on fresh fruit and vegetables have been undertaken.

The present work was carried out to study the influence of real supply chain conditions on the quality of a time-temperature-sensitive product. It was a continuity of our previous work

(Laguerre et al., 2023) in which only four instrumented cartons of mangoes were shipped from Thailand to France: two cartons by direct flight (12 h) and two cartons by indirect flight (20 h). The results showed that the fruit mass loss was lower by the direct flight due to less temperature fluctuations in the supply chain. The fruit color was also better preserved by direct flight. In this previous study, the predictive models for fruit mass loss and color change were developed based on data from nine individual fruits. Concerning the biological variability of mangoes, the validity of these models would be questionable according to the limited number of samples and the unknown carton position in the ULD container during the air shipments. This present study was, thus, conducted with the following objectives:

(i) to study the temperature distribution inside a Unit Load Device (ULD) container fully loaded by cartons of fresh mangoes along a supply chain of air transport,

(ii) to study the influence of storage temperature and duration after arrival at the destination country on mango quality, and

(iii) to validate the product mass loss model developed in our previous study by comparison with the measured data from the present study.

It is important to highlight that this study represents the first investigation of long-distance air transport with fresh produce under real conditions. The results of this study will contribute to a comprehensive understanding of temperature and relative humidity variations during air shipment and their impact on product quality. The numerical tool developed in this study can be used to predict the product quality evolution according to the temperature and humidity evolution along a supply chain. This tool would facilitate the development of guidelines for fruit exportation from Thailand to international markets.

2. Materials and methods

2.1 Mango supply chain

Mango fruits (*Mangifera indica* L. cv. 'Nam Dok Mai Si-Thong') were procured from an orchard in Chachoengsao province, Thailand (13°46′55.9″N, 101°28′ 30.1″E). The fruits were harvested 110 days after the fruit set (80-90% maturity) on April 16, 2023. After de-sapping, the fruits were delicately arranged in 20-kg plastic bins and transported to a packing house in Chonburi province (13°27′23.0″N, 101°19′08.9″E) on the next day by a non-refrigerated pickup truck (55 km ~ about 1 h travel time from the orchard). The average ambient temperature during these periods was about 30 °C (Meteostat).

Upon arrival at the packing house, the fruits were cleaned and sorted based on their weight (300–400 g) and external appearance (no blemishes and disease symptoms). The fruits underwent vapor heat treatment (core temperatures hold at 47 °C for 20 min) to kill the fruit fly larvae. Fourteen fruits were packed in a carton (**Fig. 1**). A total of hundred and eighty cartons were prepared.

Thirty-two cartons (Group 1, G1) were transported to KMITL laboratory in Bangkok on the same day by a non-refrigerated truck (~2 h travel duration). Upon arrival, all cartons were evenly divided into two sub-groups, as depicted in **Fig. 2**: one sub-group was stored at 15.5 ± 0.2 °C/70.8 ± 2.8%RH (G1/15), while the other sub-group was kept at 21.1 ± 0.1 °C/58.7 ± 5.0%RH (G1/20). The remaining cartons (Group 2, totaling 148 cartons) were stored in the cold room at a set temperature of 15 °C at the packing house and transported to Suvarnabhumi Airport (BKK) the following day via a refrigerated truck with a set temperature of 15 °C. Due to a practical problem, there was no measurement of air temperature and relative humidity in the cold room and the refrigerated truck, only the set temperatures were presented here. In fact, the involvement of multiple operators from various companies in these two steps might generate a significant risk of sensor loss when they were installed outside the cartons.

At the airport cargo terminal, the consignment underwent the pre-shipment inspection for agricultural produce and customs clearance. The indices of carton position were noted on the top wall of each carton e.g., C1H1 for the carton at column 1/height 1, then, all cartons were loaded in a ULD (type LD3/AKE) with an arrangement pattern as shown in **Fig. 3**. By this way, the positions of all cartons in the ULD were known for further analysis. The ULD was covered with plastic wrap, transferred to a tarmac, and loaded onto an aircraft (Boeing 777-300ER). It is to be emphasized that it was not possible to know the ULD position on the aircraft. The consignment was transported via a 12-h direct flight from Bangkok to Paris. Upon arrival at Paris Charles de Gaulle Airport (CDG), the consignment went through the post-shipment inspection and customs clearance. It was then transported to INRAE laboratory in Antony, a suburb of Paris (about 45 km from CDG), by a non-refrigerated truck on the same day. At the laboratory, 32 cartons were used for quality evaluation and divided equally into two sub-groups, as shown in **Fig. 2**: one sub-group was stored at 16.1 ± 0.3 °C/65.4 ± 2.9%RH (G2/15), while the other sub-group was kept at 21.6 ± 0.3 °C/64.8 ± 4.2%RH (G2/20). The timeline of each activity in the supply chain is summarized in **Table 1**.

It needs to be emphasized that the optimal storage temperature for most tropical fruits typically ranges between 10 and 13 °C. Too low temperatures may lead to fruit discoloration, which manifests as chilling injury symptoms due to biological reactions (Penchaiya et al., 2020). To avoid the risk of chilling damage caused by frequent on/off compressor operations, the storage temperature of 16 °C was used in the present study. Additionally, the storage temperature of 21 °C was chosen for its widespread implementation in commercial practices. The deviations of about 0.2-0.3 °C from these temperatures observed in storage rooms at both laboratories were attributable to technical limitations in the temperature controllers of the refrigeration systems.

2.2 Temperature and relative humidity measurements

Data loggers (iButton DS1922L, accuracy ±0.5 °C; iButton DS1923, accuracy ±0.5 °C and ±5 %RH) were used to measure air temperature, fruit (peel) temperature, and air relative humidity along the supply chain. All data loggers were previously calibrated with a high precision thermostatic oil bath (Fluke 7340, temperature stability of ±0.005 °C). The instrumentation was undertaken at the packing house. As shown in **Fig. 1b**, two data loggers were installed in an instrumented carton: one was attached to the fruit surface with aluminum tape for fruit temperature measurement (F) and the other one to the hole net for ambient temperature/relative humidity measurement (A). All data loggers started to record at 5-min intervals just before they were installed in the cartons. There were 27 instrumented cartons in total.

To investigate air and fruit temperature variations in the ULD during the flight, all instrumented cartons were deliberately placed at specified positions as shown in **Fig. 3b**. These positions involved the cartons at 3 heights (H1, H7, and H12) of 7 columns (C1, C2, C4, C6, C7, C8, and C9) and at 2 heights (H1 and H7) of 3 columns (C11, C12, and C14).

2.3 Fruit quality evaluation

The quality evaluation aimed to study (1) the influence of the carton positions in the ULD during the flight called “first study” and (2) the influence of the storage temperatures after arrival called “second study”.

The mango quality attributes including mass loss, peel color, and visual appearance were measured by non-destructive techniques while the total soluble solids (TSS) and acidity level (pH) were measured by destructive techniques. The explanation of measurement protocol is in the following sub-sections. The mass and the peel color of the fruits measured at the packing house before being packed in the cartons were considered as initial values (day 0). Subsequent measurements were undertaken on the mangoes (G2, **Fig. 1**) the day after arrival at the laboratory in France (day 3) and every 3 days over the 15-day storage (days 6, 9, 12, and 15) in two storage conditions (16.1 °C/65.4%RH and 21.6 °C/64.8%RH). To better highlight the influence of air transport, the same quality measurement was performed on the mangoes (G1, **Fig. 1**) stored at KMITL laboratory in Thailand.

For the first study, it was expected that the fruits in the carton situated in the center (C6H7) and at the corner of the ULD (C1H1 and C1H7) would expose to critical temperature conditions during the flight, i.e., heat accumulation in the center due to heat of respiration released from fruit and low air ventilation. Moreover, the cartons C1H1 and C1H7 were exposed to large temperature variations at the corner due to the vicinity of the canvas cover and the walls. Based on this hypothesis, all fruits in these three cartons were used for the quality evaluation (n = 14 per carton). According to the high number of mangoes, only the non-destructive approach was used to assess the quality evolution in this study.

For the second study, we randomly sampled three fruits from different cartons for quality evaluation under each storage condition (n = 3 per storage condition). Both non-destructive and destructive approaches were employed for quality measurement. The decision to use a limited number of replicates in this study was motivated by the abundance data in the literature regarding the impact of storage temperature on the quality of the mango cultivar 'Nam Dok Mai Si Thong' (Nampila et al., 2022; Penchaiya, 2018; Phakdee and Chaiprasart, 2020). In these studies, a high number of replicates were employed for each evaluation day. To validate the results obtained in the present study, parallel experiments conducted in Thailand by KMITL laboratory. We used 5 and 14 fruits per storage condition for destructive and non-destructive measurements, respectively.

2.3.1 Mass loss

A digital scale (CPA34001P, Sartorius, Aubagne, France) with 0.1 g accuracy was used for the measurement. Mass loss of each fruit was calculated as the percentage difference between the initial value (m_0) and the one measured on a given day (m):

$$ML = (m_0 - m)/m_0 \times 100 \quad (1)$$

2.3.2 Peel color

The peel color of the fruit was measured based on the CIELAB color scale by using a spectrophotometer (CM-700d, Konica, Tokyo, Japan). The values of L^* (100 = white; 0 = black), a^* (positive = redness; negative = green), and b^* (positive = yellow; negative = blue) were determined by placing the sensor at three points along the length on two sides of a raw fruit with peel. Precaution was undertaken to place the sensor on the same points along the measurement in different days. The average values of the six points were calculated for each fruit. The yellow index (YI) representing the yellowness of the fruits was also calculated by using the following equation (Hirschler, 2012):

$$YI = 142.86(b^*/L^*) \quad (2)$$

2.3.3 Visual appearance

Visual appearance of each fruit was evaluated by two trained panels based on two visual rating scales of shriveling and decay (Srisawat et al., 2022). The average scores by the panels for each fruit were reported. A rating of 3 was considered as the limit of saleable acceptability for both visual appearances.

2.3.4 Total soluble solids and acidity level

Total soluble solids (TSS) and acidity level (pH) were measured from the juice of the fruits. Three fruits were sampled from different cartons kept under each storage condition. Each fruit was peeled, sliced, blended, and squeezed through a filter cloth to extract its juice. TSS was determined by using a digital refractometer (PAL-BrixAcid1, Atago, Tokyo, Japan, accuracy ±0.2%Brix) and pH by a digital pH meter (Starter 300, Ohaus, Parsippany-Troy Hills, NJ, USA, accuracy ±0.01 pH). Individual fruit juices were measured three times.

2.3.5 Statistical analysis

Data were reported as the mean of 14 replicates for the “first study” and 3 replicates for the “second study” (1 fruit = 1 replicate) ± standard deviation. Statistical analysis of differences among variables was performed by IBM SPSS Statistics software (version 21) with one-way ANOVA and Tukey’s multiple comparison test. Significance was reported at the 95% confidence level ($p < 0.05$).

2.4 Mass loss model

The mass loss of mango was predicted using a model developed in Laguerre et al. (2023). This model is based on the difference in water vapour concentration between the mango peel ($C_{w,p}$) and the surrounding air ($C_{w,a}$) as given in Eq. (3):

$$\frac{dm_w}{dt} = k_{ta}A\left(C_{w,p} - C_{w,a}\right) \quad (3)$$

where k_{ta} is the water transfer coefficient between the mango (including mango peel resistance) and the surrounding air (3.01×10^{-4} m·s^{-1}, Laguerre et al. (2023)), and A is the product surface area (2.60×10^{-2} m^2, an average of 20 mangoes). The water vapour concentration of the product ($C_{w,p}$) value is calculated from the saturated vapor pressure at the product surface temperature $P_{sat}(T_s)$.

The model validation was conducted by comparing the measured and predicted results of mass loss. Root-mean-square error (RMSE) and mean relative error (MRE) were calculated and reported:

$$RMSE = \sqrt{\frac{\sum_{i=1}^{N}\left(m_{L,meas,i} - m_{L,pred,i}\right)^2}{N}} \quad (4)$$

where N is the number of measurements ($N = 6$).

3. Results and discussion

3.1 Time-temperature profile along a supply chain

To illustrate the effect of height of cartons in the ULD during the flight, **Fig. 4** presents the evolution of air temperature (red lines in **Fig. 4a**), fruit temperature (blue lines in **Fig. 4a**) and air relative humidity (**Fig. 4b**) from the packing house to the laboratory in France for 3 cartons located at the corner, adjacent to the canvas door of the ULD (column C1) for 3 heights: top (H1), middle (H7) and bottom (H12). These temperature evolutions were compared with the one located at the center of the ULD (C6H7) where the effect of supply chain temperature is the least and stable temperature would be expected. It needs to be emphasized that the time-temperature profiles of the other instrumented cartons showed similar trends.

When the cartons were kept in the cold room of the packing house (between ❶ and ❷), the air temperature on average decreased from 29.6 °C to 17.6 °C while the relative humidity increased from 56.3% to 81.1% (**Fig. 4b**). When the absolute humidity (kg of water vapor per kg of dry air or $kg_v \cdot kg_{da}^{-1}$) was calculated by using a psychrometric chart, it was clearly observed that the moisture in the air tended to decrease over the storage period (from 0.015 $kg_v \cdot kg_{da}^{-1}$ to 0.010 $kg_v \cdot kg_{da}^{-1}$) which indicates that condensation may have occurred in the carton. The air temperatures were fluctuating according to the cycles of compressor and defrost operations in the cold room of packing house. The carton position in the cold room led to slightly different cooling rates of the fruits. The fruit temperatures decreased from 29.0 °C to 18.6 °C during 33 h cold storage. Due to greater thermal inertia, the fruit temperatures fluctuated less compared to the air temperatures.

The air temperatures surged up for about 20 min while the cartons were being transferred to the refrigerated truck (❷). On average, the air and fruit temperatures were nearly constant at 18.9 °C ($\Delta T = T_{\max} - T_{\min}$ < 2.5 °C) and 19.0 °C (ΔT < 1.0 °C), respectively, during 2 h of transport from the packing house to BKK Airport (between ❷ and ❸). The heat of respiration from fruits may explain the higher temperatures in the carton in comparison with the refrigerated transport (15 °C set temperature). It can be noticed spikes in relative humidity profiles (**Fig. 4b**) at steps ❷ and ❸, suggesting the possibility of condensation occurring during the transfer from cold to warm areas.

At the airport cargo terminal, the air temperatures constantly increased to 23.9 °C (5 °C increase) during the pre-shipment inspection of about 2 h at the loading dock (between ❸ and ❹) under ambient conditions (35 °C, Meteostat). Then, the cartons were moved into the cargo building in which the air temperature was maintained at 20 °C by air conditioning system. During the ULD build-up process (between ❹ and ❺), the air temperatures slightly decreased to 22.3 °C (1.6 °C decrease). It increased again when the ULD was moved to the tarmac at night during which the ULD was exposed to the ambient temperature (30-31 °C) for 2-3 h. Prior to takeoff (❼), the air temperature and the relative humidity in the cartons on average were 25.7 °C and 80.2%, respectively. The fruit temperatures also increased continuously from 19.0 °C (❸) to 25.0 °C (❼), probably because of the heat transmission through the ULD walls. Interestingly, the heat of respiration from fruit doesn't seem to have a noticeable impact as the temperature of the fruits in the center (C6H7) increased slower than the temperature of the fruits next to the walls (C1H1, C1H7, and C1H12). The maximum temperature difference among the fruits in the cartons just before takeoff was 2.7 °C, with the highest temperature recorded in the bottom carton (C1H12, 26.1 °C) and the lowest in the carton at the center of ULD (C6H7, 23.4 °C).

It is to be highlighted that the permission was not obtained to record the ambient temperature in the aircraft during the cruising period (between ❼ and ❽); however, it was reported that the discharge air temperature can be as low as 10 °C (National Research Council, 2002). Depending on the carton positions in the ULD, the air and fruit temperatures exhibited different profiles. Temperature stratification was observed with high temperature at the top and low temperature at the bottom. The air temperatures at higher levels (H1 and H7) slightly decreased by 2.8 °C (from 27.4 °C to 24.6 °C) whereas the one at the bottom (H12) noticeably decreased by 15 °C (from 28.1 °C to 13.1 °C). The fruit temperatures in the cartons at the higher levels (H1 to H7) increased by 3 °C during the first 4 h of the flight and remained almost constant at 28 °C until the end of the flight. The fruit temperature at the bottom exhibited almost the same trend as the air temperature, i.e., the fruit temperature decreased by 8 °C (from 26.1 °C to 18.1 °C). The explanation for such temperature variations was given in detail in **Section 3.2**.

On arrival at CDG Airport, the air temperatures tended to equilibrate with the warehouse temperature (between ❽ and ❾): increasing temperature in the lower cartons and decreasing temperatures in the upper cartons. The relative humidity fluctuated during this period, reaching a minimum value of approximately 30% in some cartons (C1H7 and C6H7). Upon the reception by a logistic company (❾), the air and fruit temperatures on average were 22.7 °C and 24.6 °C, respectively. The fruit temperatures did not change much during transport to INRAE laboratory (❿) i.e., 0.5-1.0 °C variations.

Overall, the air temperature, the fruit temperature, and the air relative humidity in the cartons across the supply chain varied in the range of 13.1-32.6 °C, 16.6-31.5 °C, and 30.6-94.3%, respectively. The lowest air and fruit temperatures detected at arrival in Paris (❽) could probably be explained by low ambient temperature in the aircraft during cruising (no authorization to measure). The highest air and fruit temperatures detected upon arrival at the packing house in Thailand (❶) can be explained by the presence of field heat after harvest and high ambient temperature due to the heat waves on that day.

3.2 In-flight spatiotemporal temperature variations

Fig. 5 shows the time-averaged temperatures of the air and the fruits during the flight in the different cartons at three heights (H1, H7 and H12) of column C1 in the ULD. It was observed that the air and the fruit temperatures in the same cartons were not much different (< 2.0 °C). When compared the cartons on the top level (H1) with those on the middle level

(H7), the difference in the air and the fruit temperatures were also not much significant (< 2.0 °C). Much lower air and fruit temperatures and small temperature difference at the bottom level (H12) were detected (~4.0 °C), compared to those at the higher levels (H1 and H7). The explanation for this difference is difficult due to the complexity of the ULD geometry i.e., 14 cartons at the higher levels (H1 to H7) and 10 cartons at lower levels (H8 to H12). In addition, the absence of the ambient temperature measurement during the flight and the unknown ULD position in the aircraft make the result interpretation not easy. It is to be reminded that large air temperature differences in the cargo deck were reported (Émond et al., 1999). In our case, it could be expected that the bottom wall of the ULD was directly contacted to the aircraft wall. Heat transmission from the aircraft exterior where the air temperature can be as low as −55 °C at the cruising altitude (National Research Council, 2002) leads to low wall temperatures. In addition, the ULD might be located near the cargo door where the thermal insulation is weaker than the other locations (Émond et al., 1999; Pelletier et al., 2018). The air temperature inside the passenger deck was controlled by the air conditioning system to meet comfort conditions e.g. 20-25 °C (Liu et al., 2021). This would explain the relatively high air and fruit temperatures in the cartons at the higher levels. The authors propose the possible thermal phenomena in the aircraft during the flight (**Fig. 6**) to explain the results (i) increase in the air and the fruit temperatures at high levels (H1 and H7), (ii) the lowest average temperatures of the air and the fruit at the bottom (carton C1H12, air = 20.4 °C and fruit = 23.9 °C), and (iii) the highest average temperature of the air and fruit at the top level (H1) e.g. cartons C1H1 (fruit = 26.8 °C) and cartons C4H1 (fruit = 26.7 °C).

During 12-hour flight, the air and the fruit temperatures at the center of the ULD did not significantly different from those at the corners of the same height (< 1.0 °C, **Fig. 5**). These results imply that the heat generated by respiration during flight is not obvious, and the ambient conditions around the ULD have a more significant impact on internal temperature variations.

3.3 Fruit quality changes

3.3.1 First study: Influence of carton positions in the ULD

The quality evolution of all fruits (n = 14) in carton C1H1, C1H7, and C6H7 is shown in **Fig. 7**. This figure shows only the results of storage condition at 21.6 °C/64.8%RH (INRAE).

During the 15-day storage, a gradual increase in mass loss was observed, rising from 3.4% on day 3 to 14.8% on day 15, indicating an average daily mass loss rate of approximately 1%.

Notably, during the initial six days, the mass loss of the fruits in carton C1H1 exhibited significant differences compared to those in cartons C1H7 and C6H7 ($p < 0.05$). Conversely, no significant differences in mass loss were observed between the fruits in cartons C1H7 and C6H7 ($p > 0.05$). This result leads to conclude that, except the cartons at the corner which have more exchange surface area with air, there were no significant differences in the mass loss of the fruits among the other cartons, thus, the influence of carton position in ULD is negligible.

The peel color parameters (L^*, a^*, b^*, and YI) of the fruits in these three cartons did not show significant differences over the storage period ($p > 0.05$). During storage, the peel color of the fruits progressively darkened, shifting from a light-yellow shade in the mature stage to a dark or golden yellow shade in the ripe stage as evidenced by a decrease in the L^* value and an increase in the b^* and YI values. This change in peel color can be attributed to the synthesis of carotenoids in the fruits (Penchaiya et al., 2020). However, starting from day 9, the b^* and YI values demonstrated a gradual decline due to the presence of bruising, anthracnose, and/or stem-end rot symptoms on the skin of some fruits within the cartons, as depicted in **Fig. 8**. This decrease in yellowness is consistent with the findings reported by Yasunaga et al. (2018), who investigated the influence of postharvest distribution and storage temperature on quality changes in mangoes (cv. 'Nam Dok Mai') imported from Thailand to Japan.

Considering the visual ratings of shriveling, the results revealed that fruits in these cartons had a saleable lifespan not more than 9 days (with a shriveling score > 3). A linear relation between the shriveling rating and mass loss was observed (**Fig. 9**). It can be concluded in our study that when the critical saleable lifespan reached 9 days, it corresponds to the fruit mass loss of almost 9%. Moreover, **Fig. 7** also shows that the decay rate increases slowly from day 3 to day 6 due to the lag time of microbial growth. Then, from days 6 to 12, the rate increases exponentially, and black areas appear rapidly, limiting product salability.

Overall, the considered position of the cartons (H1 and H7) in the ULD during the flight did not demonstrate any discernible influence on fruit quality, probably because the time-temperature profiles of the different evaluated cartons were very similar. It is worth noting that the fruits in the cartons positioned at the base (H12) were exposed to different temperature variations during the flight and high mechanical compression, which could lead to different quality changes during storage. However, this aspect was not examined in the present study, as it was not initially anticipated during the planning phase.

3.3.2 Second study: Influence of storage conditions at destination

In this study, we compared the effects of two different storage conditions on the fruit quality (16.1 °C/65.4%RH and 21.6 °C/64.8%RH in INRAE storage rooms after shipment, 15.5 °C/70.8%RH and 21.1 °C/58.7%RH in KMITL storage rooms after packing house). The results are presented in **Fig. 10**. To be concise, the integer values are used to denote storage temperatures in the following discussion, i.e., 16 °C and 21 °C.

Although the absolute humidity in the 21 °C storage room (10.4 $g \cdot kg^{-1}$) were slightly higher than that in the 16 °C storage room (7.43 $g \cdot kg^{-1}$), the fruits stored at 16 °C demonstrated significantly lower mass loss compared to those stored at 21 °C throughout the evaluation period ($p < 0.05$). This could be explained by the vapor pressure deficit (VPD) as defined in **Eq. (5)** (Thompson et al., 2002) was greater in the 21 °C storage room (VPD = 1137 Pa) than in the 16 °C storage room (VPD = 831 Pa).

$$VPD = \frac{\left(\omega_{a,sat}(T_s) - \omega_a\right)P_{atm}}{0.622} \tag{5}$$

where P_{atm} is the atmospheric pressure (101.325 kPa), ω_a is the humidity ratio (kg of water vapor per kg of dry air, $kg_v \cdot kg_{da}^{-1}$) for surrounding air, and $\omega_{a,sat}(T_s)$ is the humidity ratio for saturated air at the product surface temperature ($kg_v \cdot kg_{da}^{-1}$).

Under the 16 °C storage condition, mass loss increased gradually from 2% on day 3 to nearly 10% on day 15. Conversely, under the 21 °C storage condition, the mass loss rose from 3% to 14%. The statistical results indicated a significant difference between the two storage temperatures ($p < 0.05$) from day 6 onward. Despite not significant difference ($p > 0.05$), the fruits used in Thailand experienced greater mass loss compared to their counterparts in France at the same temperatures. This discrepancy may be attributed to variations in flow patterns and velocities within the storage facilities of the respective laboratories. The VPD in the 21 °C storage room in Thailand (VPD = 1259 Pa) were also slightly higher than that in France (VPD = 1137 Pa). Nonetheless, consistent results were obtained in both countries, highlighting that lower storage temperatures resulted in a slower rate of mass loss (0.7% per day at 16 °C, 1.0% per day at 21 °C).

The development of peel color exhibited similar trends at both storage temperatures, with no significant difference ($p > 0.05$). As the storage duration progressed, the L^* values gradually declined, while the b^* and YI values initially rose and then stabilized. A slight decrease in yellowness was observed, likely attributed to the presence of bruising and disease symptoms, as evidenced in **Fig. 11**. Despite significantly lower values ($p < 0.05$), the experiment conducted in Thailand showed consistent peel color patterns for all parameters.

The TSS content varied between 14-18 %Brix over the storage duration. No significant difference ($p > 0.05$) was found between the two storage temperatures. However, the fruits at the same storage temperature in KMITL laboratory in Thailand had significantly higher TSS than those in INRAE laboratory in France ($p < 0.05$). This rise in TSS could be attributed to the conversion of polysaccharides in the tissues to soluble sugars through the process of respiration, alongside higher sugar concentrations resulting from water loss through transpiration (Hadthamard et al., 2019). In contrast, the pH consistently increased over the storage period in all cases, averaging from 3.1 to 5.1 at 16 °C and from 2.8 to 6.1 at 21 °C. A significant difference ($p < 0.05$) was observed between the two storage temperatures as well as between the results obtained from both laboratories for the same storage temperatures. This increasing trend may be explained by the conversion of organic acids into substrates during the respiration process (Hadthamard et al., 2019).

Based on the visual evaluations of shriveling and decay, the findings revealed that the fruits stored at 21 °C had a saleable lifespan of no more than 9 days, as indicated by a shriveling score exceeding 3. In contrast, when stored at 16 °C, the fruits remained viable for up to 12 days. These results provide evidence that storing the fruits at 16 °C yields superior fruit quality in comparison to storage at 21 °C. A similar result was obtained in the evaluation conducted in Thailand.

3.4 Mass loss prediction

Fig. 12 shows the comparison between measured and predicted values of mass loss of the mango in the 3 cartons (C1H1, C1H7 and C6H7) during transport and storage at 21 °C. Overall, the model agreed well with the experimental results with RMSE of 1.4%, 1.8% and 0.4% for C1H1, C1H7 and C6H7, respectively. Only slight differences between different positions were observed, mainly because the flight was direct (loaded during the night in Thailand and unloaded in the morning in France) and few temperature variations were observed. However, these results showed that the product mass, and hence the product saleable (see **Section 3.3.1** and **Fig. 9**), can be estimated from the temperature and relative humidity measured using a thermo-button placed in the cartons. Those results would however have to be confirmed in the case of a longer transportation with temperature variations, for example, loaded in the afternoon with a delay on the ramp, or with an indirect flight with a transfer to another aircraft at an intermediate airport (e.g., Dubai).

4. Conclusions and perspectives

This study presents a field investigation of an air cargo supply chain of fresh mango from a packing house in Thailand to a laboratory in France. Air temperature, air relative humidity, and fruit temperature were measured in the mango fruit cartons across the supply chain using thermo-hygrometer data loggers. In a cargo of 148 cartons, twenty-seven instrumented cartons were placed at prescribed positions in a ULD container to observe temperature distributions during the flight.

At the destination laboratory, mango quality attributes were measured using both non-destructive (mass loss, peel color, visual appearance) and destructive (TSS and pH) approaches on different days during storage at 16 °C and 21 °C. The results revealed that fruit temperatures throughout the studied supply chain varied in the range of 16.6-30.5 °C, differing 2-3 °C from air temperatures. During the flight, the temperature profiles of the fruits in the upper cartons demonstrated stability with slight fluctuations based on their respective positions. The average variations were between 25 °C and 28 °C. In contrast, fruit temperatures in the base cartons exhibited a gradual decline from 26 °C to 20 °C.

Because of a short cruising period (12 h) in comparison to a storage duration at the destination (15 days) and proper ambient temperature condition during the experiment (direct flight, loading / unloading during the night), the results from the quality assessment during 21 °C storage did not demonstrate any discernible influence of the carton position in the ULD on fruit quality. It was also found that storing the fruits at the lower temperature (16 °C) resulted in superior fruit quality, thereby prolonging the shelf life up to 12 days compared to a shelf life of less than 9 days when stored at the higher temperature (21 °C).

In addition to the field investigation, the mass loss model developed in our previous study was used to predict mango mass loss using measured temperature and relative humidity profiles. We found good agreement between the predicted and measured data (RMSE < 1.8%). Thus, based on the percentage of critical mass loss, the model can estimate product saleable days in function of ambient temperature and humidity in the supply chain.

Field investigation is costly, time-intensive, and complex to implement, this explains few studies of air transport in literature. To avoid such disadvantages and for better understanding the physical phenomena, an experimental study in a controlled-temperature test room with a loaded ULD was undertaken. We will present in the future the measured air/product temperature evolutions at different positions and the analysis of heat transfer mode i.e., conduction and convection. In addition, the development of heat and mass transfer models in a loaded ULD is in progress using a zonal approach and Computational Fluid Dynamics (CFD). The experimental data obtained from this present study and the one in a laboratory scale (to be presented) will be used to develop and validate these models. They will allow the prediction of temperature and humidity changes in different positions of cartons in a ULD exposed to variable ambient temperature and humidity as in a real supply chain for other unexplored experimental conditions (indirect flight, temperature abuse, impact of solar radiation). The predicted data (temperature/humidity) will be integrated into the quality model to estimate product quality changes and shelf life. For a longer term, the influence of vibration along a supply chain on the product quality would be studied, which might partly explain higher product quality stored in Thailand in comparison to the one exported to France.

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References

Abad, E., Palacio, F., Nuin, M., Zárate, A.G.d., Juarros, A., Gómez, J.M., Marco, S., 2009. RFID smart tag for traceability and cold chain monitoring of foods: Demonstration in an intercontinental fresh fish logistic chain. Journal of Food Engineering 93, 394-399.
Brasil, I.M., Siddiqui, M.W., 2018. Chapter 1 - Postharvest Quality of Fruits and Vegetables: An Overview, in: Siddiqui, M.W. (Ed.), Preharvest Modulation of Postharvest Fruit and Vegetable Quality. Academic Press, pp. 1-40.
Buxbaum, P., 2018. The perils of perishable airfreight shipments. Retrieved from: https://www.ajot.com/premium/ajot-the-perils-of-perishable-airfreight-shipments (accessed 666).
Dimerco, 2021. Building airline ULDs: What you need to know. Retrieved from: https://dimerco.com/building-airline-uld-need-to-know/ (accessed 20.07.2023).
Émond, J.P., Mercier, F., Nunes, M.C.N., 1999. In-flight temperature conditions in the hold of a widebody aircraft, 20th International Congress of Refrigeration. IIR/IIF, Sydney, Australia, pp. 1-7.
Hadthamard, N., Chaumpluk, P., Buanong, M., Boonyaritthongchai, P., Wongs-Aree, C., 2019. Effects of Multilayer Coating of Chitosan and Polystyrene Sulfonate on Quality of

‘Nam Dok Mai No. 4’Mango. International Journal of Agricultural and Biosystems Engineering 13, 42-48.
Hirschler, R., 2012. Whiteness, yellowness, and browning in food colorimetry, in: Caivano, J.L., del Pilar Buera, M. (Eds.), Color in food: Technological and psychophysical aspects, 1 ed. CRC Press, Boca Raton, FL, pp. 93-103.
Laguerre, O., Duret, S., Chaomuang, N., Denis, A., Derens-Bertheau, E., Mawilai, P., Ndoye, F.T., Pongsuttiyakorn, T., Rakmae, S., Srisawat, K., Sirisomboon, P., Pornchaloempong, P., 2023. Influence of long-distance air transport conditions on horticultural product quality: Case study of fresh mango shipment from Thailand to France. International Journal of Refrigeration 152, 16-25.
Laurin, É., Nunes, M., Émond, J.-P., Brecht, J.K., 2006. Residual effect of low-pressure stress during simulated air transport on Beit Alpha-type cucumbers: Stomata behavior. Postharvest Biology and Technology 41, 121-127.
Laurin, E., Nunes, M.C.N., Émond, J.P., 2003. Forced-air cooling after air-shipment delays asparagus deterioration. Journal of Food Quality 26, 43-54.
Liu, M., Chang, D., Liu, J., Ji, S., Lin, C.-H., Wei, D., Long, Z., Zhang, T., Shen, X., Cao, Q., 2021. Experimental investigation of air distribution in an airliner cabin mockup with displacement ventilation. Building and Environment 191, 107577.
Lou, X., Sun, Y., Lv, D., Yin, Y., Pei, J., He, J., Yang, X., Cui, X., Liu, Y., Norback, D., Chen, Q., 2022. A study on human perception in aircraft cabins and its association with volatile organic compounds. Building and Environment 219, 109167.
Mai, N.T.T., Margeirsson, B., Margeirsson, S., Bogason, S.G., Sigurgisladóttir, S., Arason, S., 2012. Temperature mapping of fresh fish supply chains–air and sea transport. Journal of Food Process Engineering 35, 622-656.
Mercier, S., Villeneuve, S., Mondor, M., Uysal, I., 2017. Time–temperature management along the food cold chain: A review of recent developments. Comprehensive Reviews in Food Science and Food Safety 16, 647-667.
Nagda, N.L., Hodgson, M., 2001. Low relative humidity and aircraft cabin air quality. Indoor Air 11, 200-214.
Nampila, S., Choeichaiyaphum, C., Isarangkool Na Ayutthaya, S., 2022. Control of quality and management of rot disease by using coating and temperature controlling for ÂNam Dok Mai SithongÂ mango, 1336 ed. International Society for Horticultural Science (ISHS), Leuven, Belgium, pp. 387-394.
National Research Council, 2002. The airliner cabin environment and the health of passengers and crew. National Academy Press, Washington, DC.
Nunes, M.C.N., Emond, J.P., Brecht, J.K., 2006. Brief deviations from set point temperatures during normal airport handling operations negatively affect the quality of papaya (Carica papaya) fruit. Postharvest Biology and Technology 41, 328-340.
Pelletier, W., Chau, K.V., Bucklin, R.A., Brecht, J.K., Hahn, D.W., Émond, J.-P., 2018. Analysis of air cargo temperature variations during transport operations. Transactions of the ASABE 61, 723-732.
Pelletier, W., Nunes, M.C.d.N., Émond, J.-P., 2005. Air transportation of fruits and vegetables: an update. Stewart Postharvest Review 1, 1-7.
Penchaiya, P., 2018. Assessing of postharvest quality of mango fruit with change of texture characteristics, School of Bioresources and Technology. King Mongkut's University of Technology Thonburi.
Penchaiya, P., Tijskens, L.M., Uthairatanakij, A., Srilaong, V., Tansakul, A., Kanlayanarat, S., 2020. Modelling quality and maturity of ‘Namdokmai Sithong’mango and their variation during storage. Postharvest Biology and Technology 159, 111000.

Phakdee, N., Chaiprasart, P., 2020. Modified Atmosphere Storage Extends the Shelf Life of 'Nam Dok Mai Sri Tong' Mango Fruit. International Journal of Fruit Science 20, 495-505.
Singh, S.P., Singh, J., Stallings, J., Burgess, G., Saha, K., 2009. Measurement and analysis of temperature and pressure in high altitude air shipments. Packaging Technology and Science 23, 35-46.
Srisawat, K., Sirisomboon, P., Pun, U.K., Krusong, W., Rakmae, S., Chaomuang, N., Mawilai, P., Pongsuttiyakorn, T., Chookaew, C., Pornchaloempong, P., 2022. Temperature Difference in Loading Area (Tarmac) during Handling of Air Freight Operations and Distance of Production Area Affects Quality of Fresh Mango Fruits (Mangifera indica L.'Nam Dok Mai Si Thong'). Horticulturae 8, 1001.
Thompson, J.F., 2004. Air transport of perishable products. University of California, Agriculture and Natural Resources.
Thompson, J.F., Mitchell, F.G., Rumsay, T.R., 2002. Commercial cooling of fruits, vegetables, and flowers. UCANR Publications.
Villeneuve, S., Mercier, F., Pelletier, W., Ngadi, M.O., Emond, J.P., 2000. Effect of environmental conditions on air shipment of perishables during ground operations, ASAE Annual International Meeting. American Society of Agricultural Engineers, Milwaukee, Wisconsin, USA, pp. 1-11.
Yasunaga, E., Fukuda, S., Takata, D., Spreer, W., Sardsud, V., Nakano, K., 2018. Quality changes in fresh mango fruits (Mangifera indica L.'Nam Dok Mai') under actual distribution temperature profile from Thailand to Japan. Environmental Control in Biology 56, 45-49.
Yousuf, B., Deshi, V., Ozturk, B., Siddiqui, M.W., 2020. 1 - Fresh-cut fruits and vegetables: Quality issues and safety concerns, in: Siddiqui, M.W. (Ed.), Fresh-Cut Fruits and Vegetables. Academic Press, pp. 1-15.

Table 1 Shipment schedule.

No.	**Activity**	**Date**	**Local time of Thailand** (hh:mm)	**Duration between the current and preceding activities**	**Source of data**
0	*Arrival at the packing house*	*17/04/2023*	*08:20*	*0*	*KMITL researcher*
1	*Cold storage (15 °C) at the packaging house*	*18/04/2023*	*17:30*	*33.2 h*	*Temperature profile from the temperature recorders*
2	*Transport by a refrigerated truck (15 °C) from the packing house*	*19/04/2023*	*13:30*	*20.0 h*	*Logistics provider*

3	*Arrival at Suvarnabhumi Airport (BKK)*	*19/04/2023*	*15:30*	*2.0 h*	*Logistics provider*
4	*ULD build up in the airport cargo terminal*	*19/04/2023*	*17:40*	*2.2 h*	*KMITL researcher*
5	*Transfer the ULD to the tarmac*	*19/04/2023*	*19:40*	*2.0 h*	*Temperature profile from the temperature recorders*
6	*Loading the ULD onto the aircraft (Boeing 777-300ER)*	*19/04/2023*	*22:30*	*2.8 h*	*Shipping record*
7	Departure from the airport (BKK)	20/04/2023	00:20	1.8 h	Boarding pass (TG930) and shipping record
8	**Arrival at Charles de Gaulle Airport (CDG)**	**20/04/2023**	**12:20**	**12.0 h***	**Boarding pass (TG930)**
9	**Transport by a non-refrigerated truck from the airport (CDG)**	**20/04/2023**	**21:00**	**8.7 h**	**Logistics provider**
10	**Arrival at INRAE**	**20/04/2023**	**22:30**	**1.5 h**	**INRAE researcher**

In Italic, activities in Thailand. **In bold, activities in France.**

Flight time accounted for 14% of the total shipment time (86.2 h).

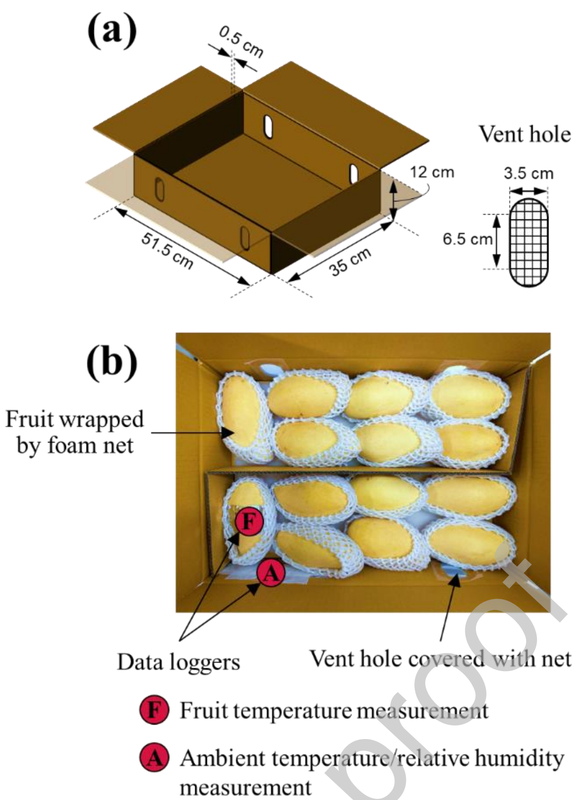

Fig. 1 (a) Carton dimensions and (b) position of data loggers in the instrumented carton.

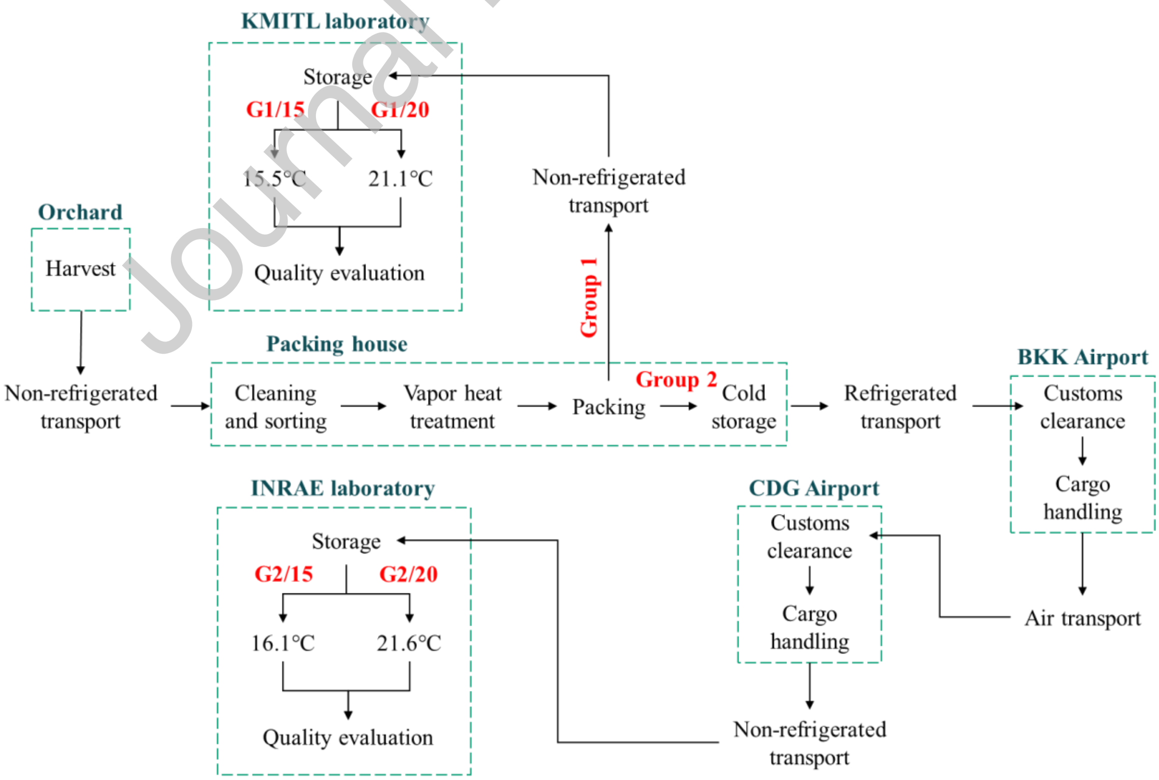

Fig. 2 The mango supply chain in this study.

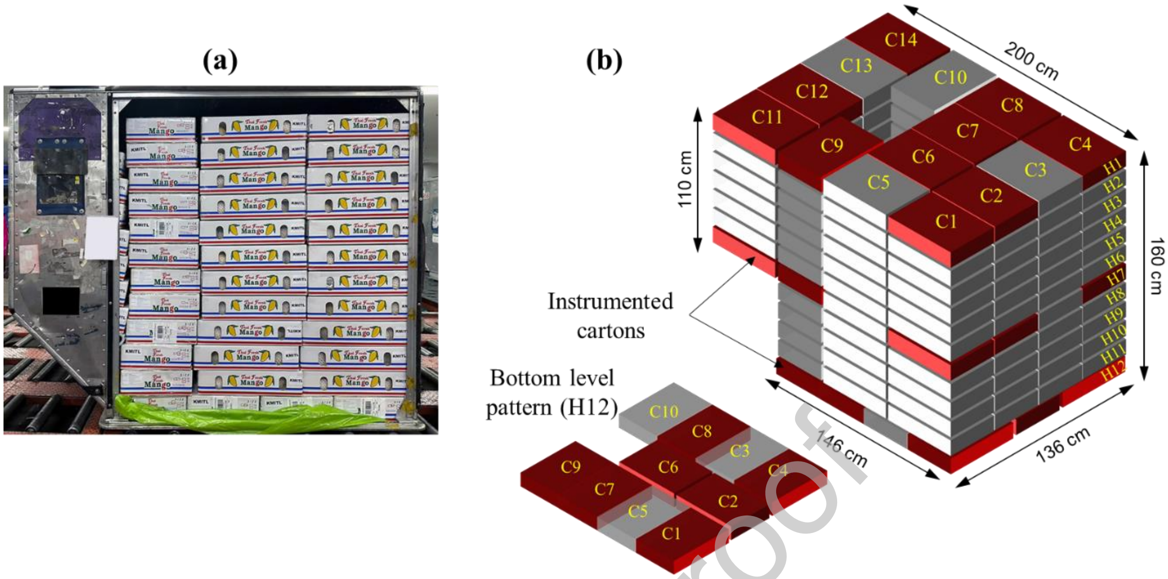

Fig. 3 (a) Photograph of the ULD after finished the build-up and (b) pattern of carton stacking in the ULD. Red cartons are instrumented with data loggers.

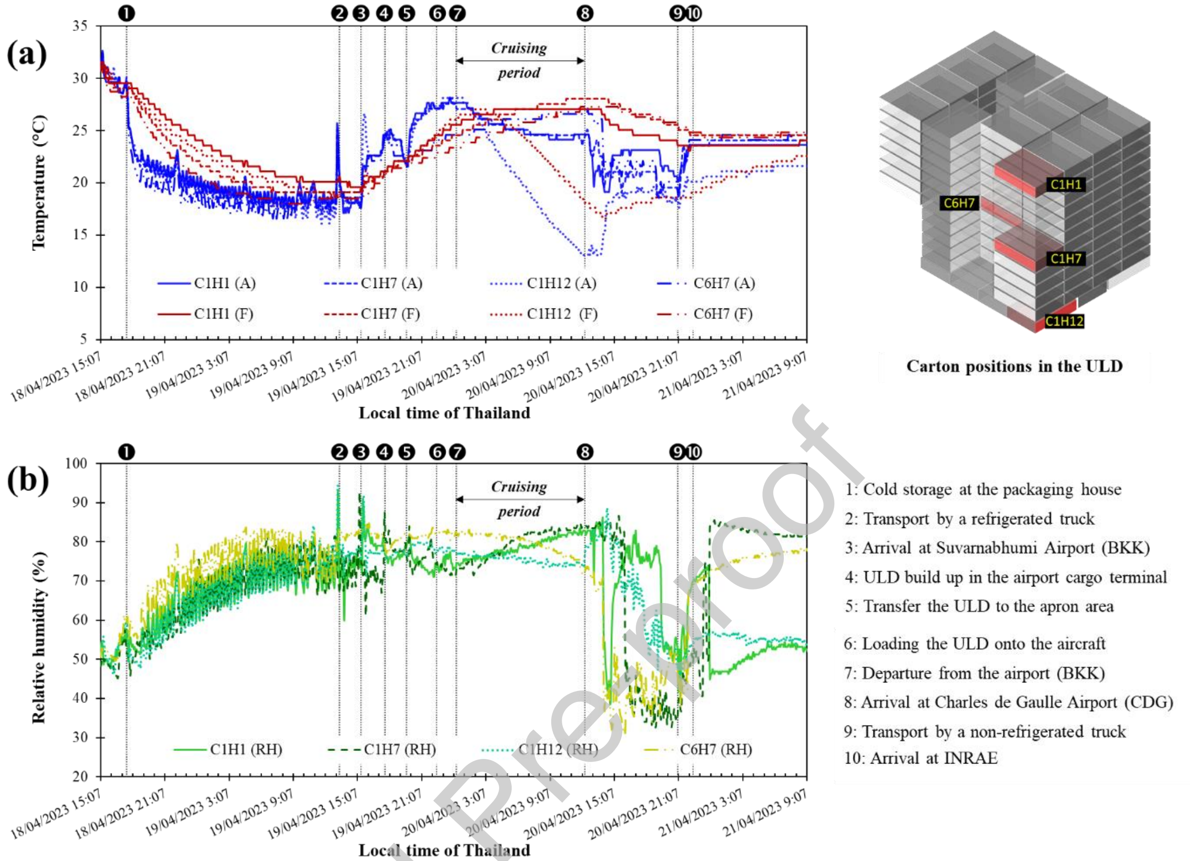

Fig. 4 Evolution of (a) air (A) and fruit (F) temperatures, and (b) air relative humidity (RH) across the supply chain in the four cartons at different positions in the ULD (C1H1, C1H7, C1H12, and C6H7).

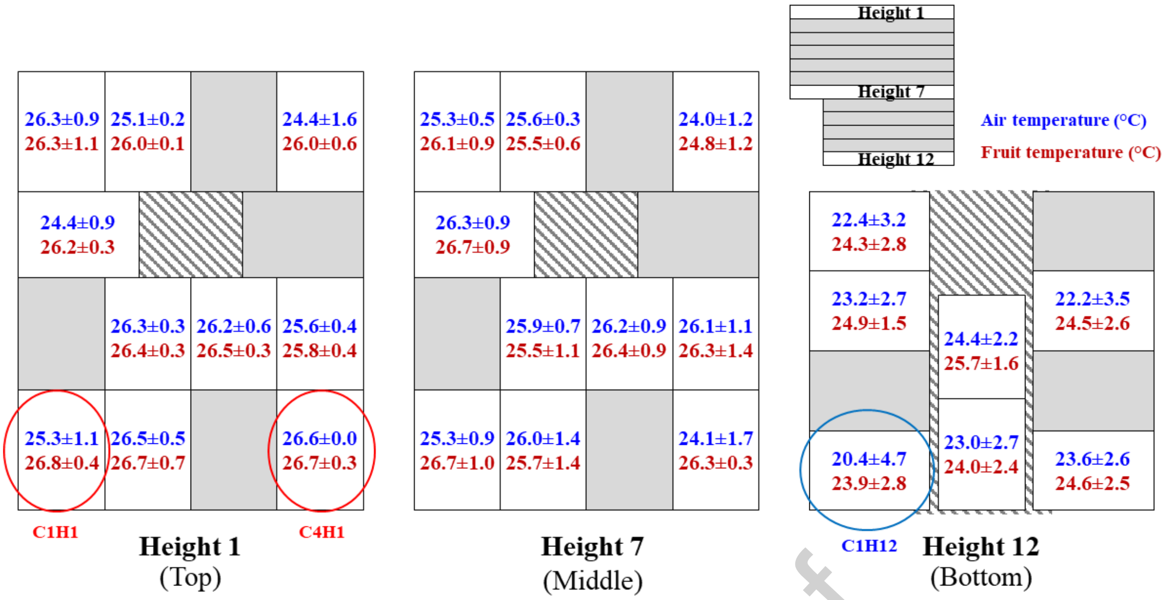

Fig. 5 Time-average ± standard deviation of air (in blue) and fruit (in red) temperatures in different cartons at the top (H1), the middle (H7) and the bottom (H12) in the ULD during the flight.

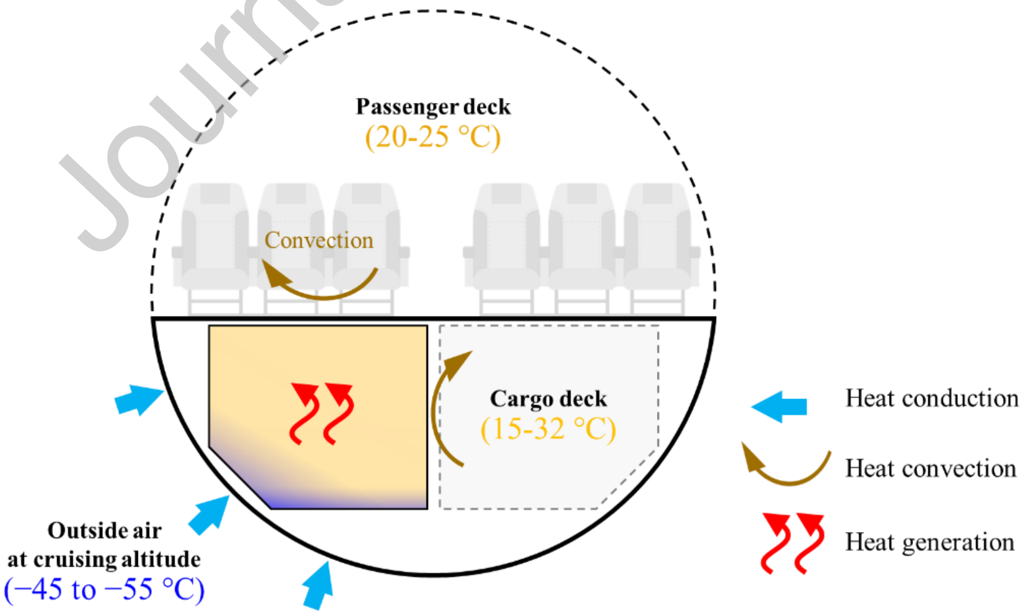

Fig. 6 Cross-section representation of a passenger aircraft with notional thermal phenomena during the flight.

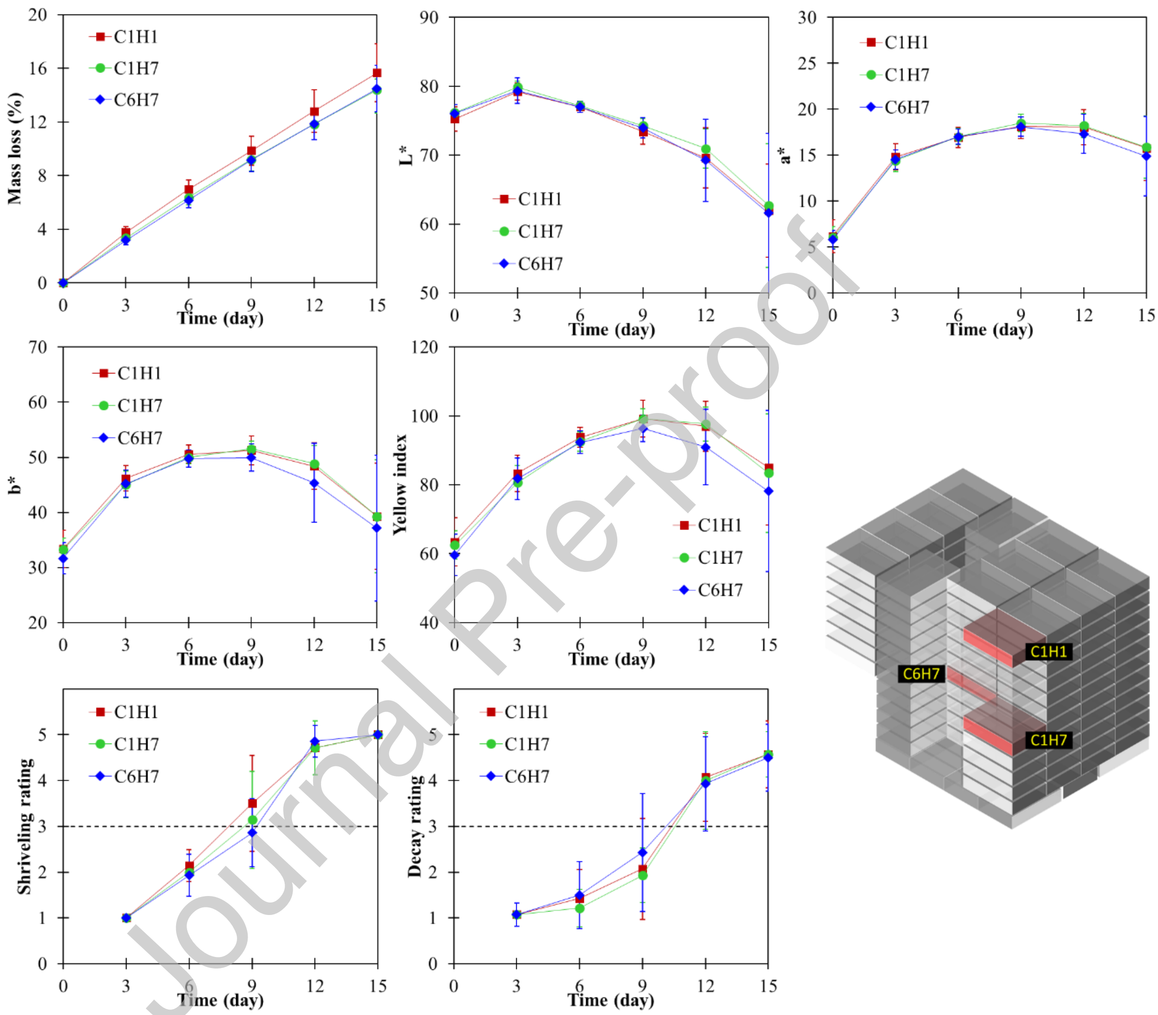

Fig. 7 Quality changes of the fruits in the cartons at three positions in the ULD over 15-day in 21 °C storage room of INRAE laboratory after arrival to France. Data are the mean of 14 fruits and the bars represent the standard deviation.

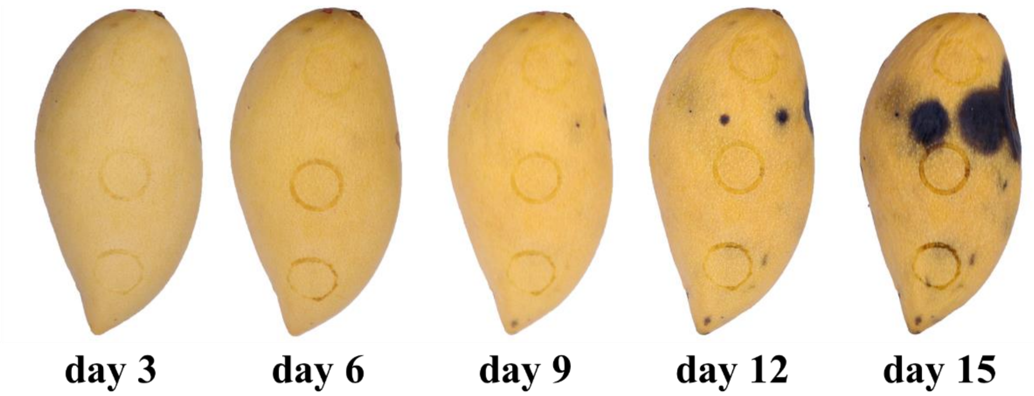

Fig. 8 Visual appearance of the fruits in carton C6H7 during 15-day in 21 °C storage room of INRAE laboratory.

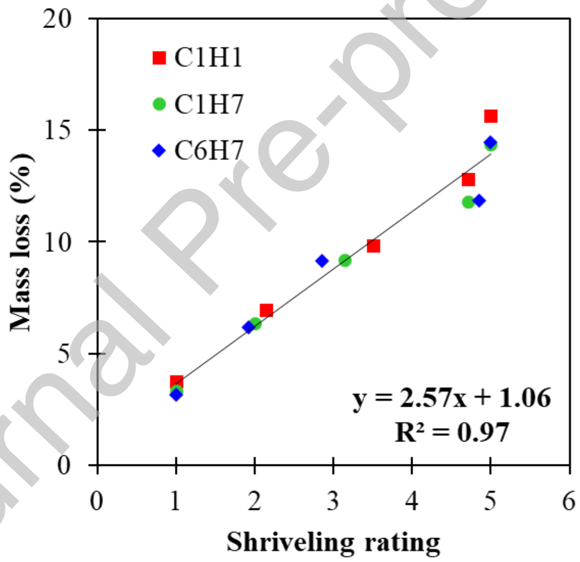

Fig. 9 Linear relation between shriveling rating and mango mass loss.

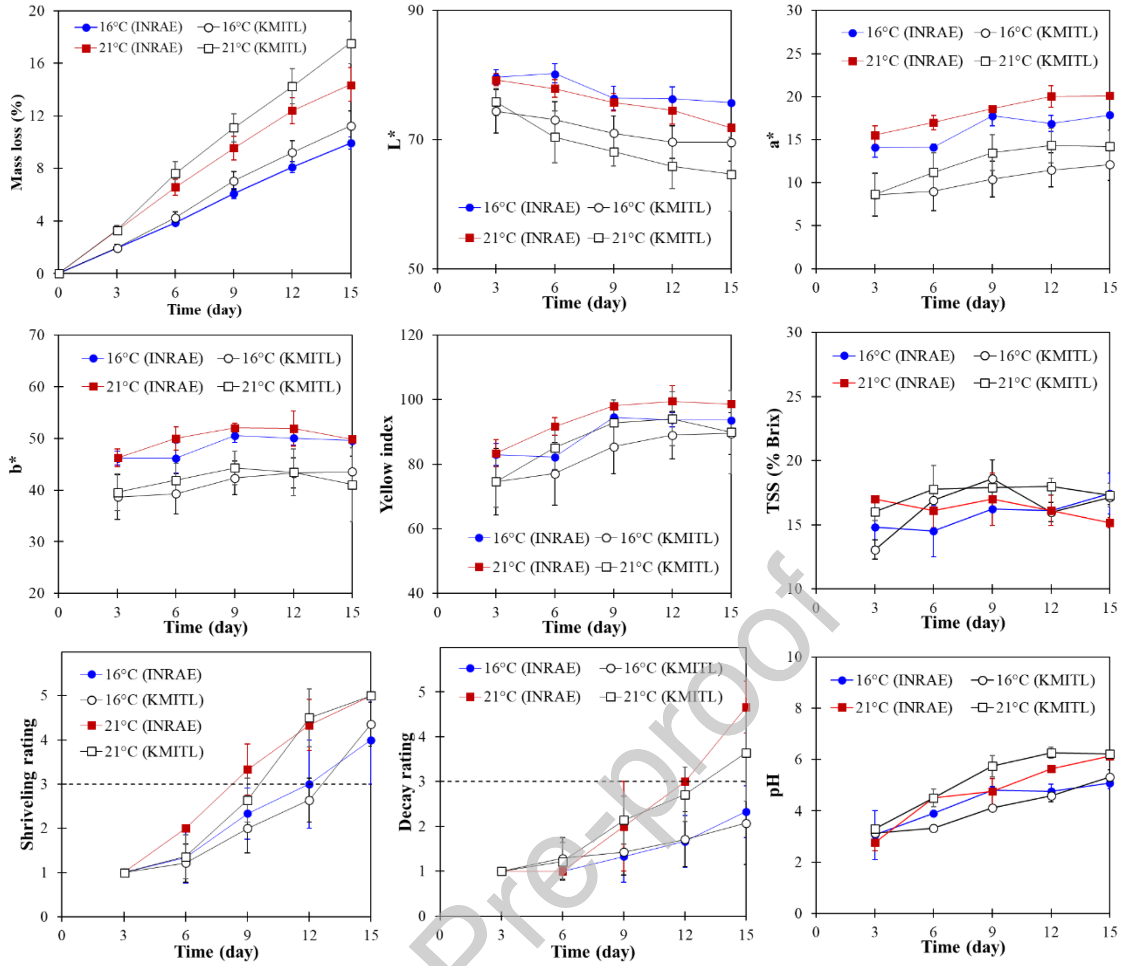

Fig. 10 Quality changes of the fruits over 15-day in the 16 °C and 21 °C storage rooms of INRAE and KMITL laboratories. Data are the mean of 3 fruits and the bars represent the standard deviation.

Fig. 11 Visual appearance of the fruits kept in INRAE storage rooms at (a) 16 °C and (b) 21 °C.

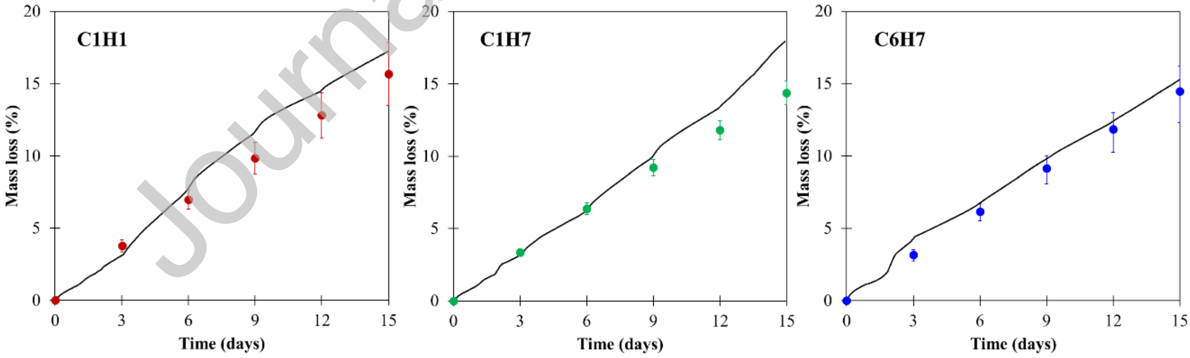

Fig. 12 Comparison between measured (points) and predicted values (solid line) of mass loss during ULD transportation and storage at 21 °C.

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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