APPLICATION OF ROOM COOLING AND THERMAL INSULATION MATERIALS IN COOL CHAIN MANAGEMENT OF OKRA

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MASTER OF SCIENCE
IN
POSTHARVEST TECHNOLOGY AND INNOVATION

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ABSTRACT

Temperature and relative humidity (RH) fluctuations during storage and transportation cause wilting and heat damage before processing of okra during storage and transportation. This work was the first to study room cooling and thermal-insulation materials for cool chain management for reduction of postharvest losses of okra and other perishable crops.

In the first trial, a typical handling (TP) and covering with perforated linear low-density polyethylene (P-LLDPE) without room cooling were employed as control treatments compared with developing handling (DH). After either room cooling at 0 °C for 2 h or no cooling, the okra pods were covered with three different materials: 1) perforated linear low-density polyethylene (P-LLDPE), 2) two layers of heat reflective sheet with thin nonwoven (HRS+TNNW), and 3) metalized foam sheet (MFS). After room cooling, HRS+TNNW and MFS covers (10 h) delayed a rise of pulp temperature to reach 18 °C, compared to P-LLDPE (2 h). TP treatment had highest postharvest

losses (mass loss and the incidence of decay) (65%), followed by P-LLDPE without cooling (59%), MFS without cooling (52%), MFS with cooling (27%), HRS+TNNW without cooling (26%), and HRS+TNNW with cooling (15%). Room cooling demonstrated an important pretreatment before applying thermal insulation covers to delay an increase of temperature and to protect heat accumulation.

In the second trial, efficiency of different thermal insulation materials to minimize temperature rise and fluctuation was determined. Room cooling at 0 °C for 2 h was applied in okra samples before covering. Four thermal insulation covering materials: (1) heat reflective sheet with thin nonwoven (HRS+TNNW), (2) heat refractive sheet with thick nonwoven (HRS+TKNW), (3) metalized Tyvek® (MTyvek) and (4) metalized foam sheet (MFS) were studied and compared with perforated linear low-density polyethylene (P-LLDPE) and no cover as control treatment. The material properties including thickness, thermal heat energy (Q_x), thermal resistance (R-value), air permeability and water vapor permeability (WVP) were investigated. The proper thermal insulation material for okra covering should have low Q_x, high R-value and moderate WVP values. HRS+TNNW and HRS+TKNW had the lowest rate of air and pulp temperature changes. HRS+TNNW cover (5%) exhibited the lowest postharvest losses followed by HRS+TKNW (10%), P-LLDPE (11%), MFS (13%), no cover (18%) and MTyvek (23%), respectively.

In conclusion, the combination of room cooling and HRS+TNNW exhibited the greatest efficiency for maintaining cool temperature and minimizing postharvest loss of okra during simulated storage and transportation. HRS+TNNW prototype had good performance in terms of material and okra quality comparable to the commercial cover (MFS). In future study, HRS+TNNW is suggested to improve material functions or properties to apply in okra and other fresh produce.

Keywords: Covering Material, Decay, Metalized Foam Sheet, Nonwoven, Okra, Postharvest Loss

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ABBREVIATIONS AND SYMBOLS

CFB	Corrugated fiberboard
DH	Developing handling
EPS	Expanded polystyrene
HRS	Heat refractive sheet
MFS	Metalized foam sheet
MTyvek	Metalized Tyvek®
P-LLDPE	Perforated linear low-density polyethylene
PP	Polypropylene
RH	Relative humidity
RR	Respiration rate
Q_{10}	Temperature coefficient
R-value	Thermal resistance
Q_x	Thermal heat energy
TKNW	Thick nonwoven
TNNW	Thin nonwoven
TP	Typical handling
WVP	Water vapor permeability

CHAPTER 1

INTRODUCTION

1.1 Background

Okra (*Abelmoschus esculentus* L.) is a vegetable crop, under the Malvaceae family, that is grown seasonally [1]. It is widely grown throughout tropics and subtropics, including Africa, Asia, Southern Europe, and North America [2]. Okra pods are green in color, tender, and have 5 ridges with a length of 6–8 cm. Okra should be harvested about 6 days after flowering for optimal maturity [3]. Okra is a major exported vegetable crop of Thailand. Japan, Hong Kong, Switzerland, Germany, and the United Arab Emirates are the main importer of fresh okra from Thailand, particularly Japanese market accounted for 82.6% of the total exported okra volume (about 5.50 million USD). Thailand's Centre and northern regions are the primary growing regions [4]. Poor harvesting practice, inadequate pre-cooling facilities, as well as poor handling and road condition during transportation are all associated with the quality of okra [5].

Okra is a perishable fruit that has high moisture content and high respiratory activity. Okra is extremely sensitive to water loss, color fading and breakdown, thus leading to economic and commercial losses and unacceptable quality for consumer [6]. Due to high respiration rate in okra, temperature is the main environmental factor influencing its postharvest quality. In order to increase shelf life of okra from 7 to 10 days, storage conditions such as temperature and humidity should be maintained at 7 to 10 °C with RH of 95 to 100% [7]. After 5 days, mass losses of okra stored at 5 °C, 10 °C, and 25 °C were 10%, 16%, and 27%, respectively [8]. In addition, when the storage temperature was raised to 25-27 °C, the respiration rate increased (328-362 mg CO_2 kg^{-1} h^{-1}) compared to 4-5 °C storage (53-95 mg CO_2 kg^{-1} h^{-1}) [7].

The temperature-control process during supply chain is known as a cool chain management to maintain the quality of fresh produce [9]. The continuous exposure of fresh product to the proper air temperature and RH is critical to the successful use of cool chain [10]. In fresh produce, heat production, also known as 'Vital heat' is generated as a by-product, mainly as a result of the respiration process [11]. In order to remove as much heat as possible from fresh produce and preserve the fresh produce at highest quality, producers should cool the fresh produce as soon as possible after harvest [12]. For the processing of exported okra, forced-air cooling was suggested for heat removal after harvesting [13]. Export okra from India was cooled to 15 °C by room cooling before storage at 8 °C [14]. Without cooling, fresh produce quality was reduced, and fruit deterioration was enhanced. When no cooling was used throughout the whole storage and transportation chain, postharvest loss of commercial fresh produce increased by 25–30 %, whereas it only increased by 5–10 % when a pre-cooling at 8 °C was used [15]. Only a few studies have investigated the effects of various cooling methods on reduction of heat production in okra, as well as their effect on increasing quality and shelf life.

In order to prevent or minimize temperature fluctuations in a system or environment, thermal insulation materials help delaying the transfer of heat [16]. Pallet covers have been used as thermal insulation materials, in combination with other materials, while transporting fresh produce [17]. By reducing temperature and humidity fluctuations during the transportation of fresh produce, pallet covers are an alternative packaging technology that helps to minimize loss from food deterioration [18-19]. The beneficial effect of pallet covers on reducing postharvest losses of fresh produce were investigated in amaranth [17], chard, cucumber, carrot [19], and strawberries [20]. Covering with thermal insulation material showed better temperature preservation and slower temperature changes than with no cover [17,19-20]. The thickness, number of surfaces, and number of reflective surfaces of a material are all essential variables in determining its insulating ability [21]. The main thermal insulation properties are determined by measuring the amount of heat transfer and the thermal resistance (R-value). The process of energy flow owing to temperature variations between two sources is known as heat transfer [22]. Reduced conductive heat loss indicates greater

insulation of the materials with a low rate of heat transfer [23]. In contrast, a higher R-value indicates greater thermal insulation performance [24]. Nevertheless, there seem to be a few studies on the use of thermal insulation covers to minimize postharvest losses of okra under various temperature environments.

Domestic transportation of okra from a community enterprise in Phayao province (northern Thailand) to food factories (central Thailand) resulted in postharvest losses of okra due to temperature and RH fluctuations in the transportation vehicle, which caused wilting heat damage and decay. Inadequate cooling facilities, such as no pre-cooling, cool storage, and transportation in an unrefrigerated vehicle, cause physiological loss. In recent years, less academic research has been performed in cool chain management, cooling of okra, and thermal insulation materials for cool chain management of fresh products. Particularly, there has been no reported in Thailand on okra cooling, thermal insulation materials, or cool chain management. Thus, this current research focused on the feasibility study of thermal insulation covering in okra during simulation storage and transportation as a practice for community enterprise in Phayao province. Also, the room cooling will be applied in pre-treatment before simulated storage to reduce heat of okra. The developing cool chain management (room cooling and thermal insulation covering) may decrease postharvest losses and maintain temperature fluctuation during simulated storage and domestic transportation.

1.2 Objectives

The main objectives of this research were:

1.2.1 To evaluate the efficiency of room cooling combining with thermal insulation materials in controlling cool temperature and okra quality under simulated storage and transportation.

1.2.2 To investigate the performance of different thermal insulation covering materials on controlling temperature fluctuation under storage and transportation temperature conditions.

1.3 Research Hypotheses

This thesis study examined the two research questions via two experiments, which were applied room cooling and thermal insulation materials for developing postharvest handling of okra

1.3.1 It was expected that using room cooling as a pre-treatment would reduce okra heat and postharvest losses of okra under simulated storage and transportation.

1.3.2 It was expected that thermal insulation cover would reduce temperature fluctuation, delayed senescence and postharvest losses of okra as, compared to perforated linear low-density polyethylene (P-LLDPE) under simulated storage and transportation.

1.4 Research Scope

1.4.1 To study the effects of room cooling combined with thermal insulation material on the quality changes of ‘Lady Finger’ okra during simulated storage and transportation.

1.4.2 To investigate imparts of different thermal insulation materials; thin nonwoven (TNNW), thick nonwoven (TKNW), heat reflective sheet (HRS), metalized Tyvek® (MTyvek) and metalized foam sheet (MFS), as compared to perforated linear low-density polyethylene (P-LLDPE) and no covering, on ‘Lady Finger’ okra quality and temperature controlling during simulated storage and transportation.

References

[1] Siemonsma, J. S. (1982). West African okra—Morphological and cytogenetical indications for the existence of a natural amphidiploid of *Abelmoschus esculentus* (L.) Moench and A. *manihot* (L.) Medikus. *Euphytica, 31*, 241–252.

[2] Tripathi, K. K., Warrier, R., Govila, O. P., & Ahuja, V. (2011). Biology of *Abelmoschus esculentus* L. (okra). *Series of Crop Specific Biology Documents*. New Delhi, India: Ministry of Environment and Forests Government of India.

[3] Barnwal, A. K., Pal, A. K., Tiwari, A., Pal, S., & Singh, A. K. (2017). Effect of Picking Stages on Fruit and Seed Development in Okra [*Abelmoschus esculentus* (L.) Moench] Cultivars Kashi Pragati and Kashi Kranti. *International Journal of Agriculture, Environment and Biotechnology*, *10*(6), 695-702. doi: 10.5958/2230-732X.2017.00086.9

[4] Thai Customs. (2021). *Statistic report 2020*. Retrieved February 12, 2021, from http://www.customs.go.th/statistic_report.php?lang=en&tariff_code=07099990003

[5] Tsado, E. K. (2015). Quality of postharvest handling of marketable okra fruits sold in Minna, Niger state, Nigeria. *European Journal of Agriculture and Forestry Research*, *3*(5), 33-45.

[6] Huang, S., Li, T., Jiang, G., Xie, W., . . . Duan, X. (2012). 1-Methylcyclopropene reduces chilling injury of harvested okra (*Hibiscus esculentus* L.) pods. *Scientia Horticulturae*, *141*, 42-46. doi: 10.1016/j.scienta.2012.04.016

[7] Perkins-Veazie, P. (2016). Commodity summaries: Okra. In K. C. Gross, C. Y. Wang & M. Saltveit (Eds.), *The Commercial storage of fruits, vegetables and florist and nursery stocks* (pp. 430–432). Washington: United States Department of Agriculture (USDA).

[8] Finger, F. L., Della-Justina, M. E., Casali, V. W. D., & Puiatti, M. (2008). Temperature and modified atmosphere affect the quality of okra. *Scientia Agricola*, *65*, 360-364.

[9] Greis, N. P. (2011). *Management the "Cool Chain" A Cold Chain is Only as Cool as Its Warmest Link*. Retrieved September 10, 2021, from https://www.asia coldchainshow.com/uploads/Managing%20the%20Cool%20Chain.pdf

[10] Florkowski, W. J., Prussia, S. E., Shewfelt, R. L., & Brueckner, B., (2009). *Postharvest Handling: A Systems Approach* (2nd ed.). San Diego: Academic Press.

[11] Kader, A. A., & Saltveit, M. E. (2003). Respiration and gas exchange. In J. A. Bartz & J. K. Brecht (Eds.), *Postharvest Physiology and Pathology of Vegetables* (2nd ed, pp. 7–29). New York: Marcel Dekker Inc.

[12] Kienholz, J., & Edeogu, I. (2002). *Fresh fruit & vegetable pre-cooling for market gardeners in Alberta*. Woodlands: Alberta Agriculture, Food and Rural Development.

[13] Food and Agriculture Organization. (2012). *Good practice in the design management and operation of a fresh produce packing-house*. Retrieved September 9, 2021, from https://www.fao.org/3/i2678e/i2678e00.pdf

[14] Dhall, R. K., Sharma, S. R., & Mahajan, B. V. C. (2014). Development of post-harvest protocol of okra for export marketing. *Journal of Food Science and Technology*, *51*(8), 1622-1625.

[15] Yang, Z., Ma, Z., Zhao, C., & Chen, Y. (2007). Study on forced-air pre-cooling of longan. In *2007 ASAE Annual Meeting* (p. 1). Michigan: American Society of Agricultural and Biological Engineers.

[16] Deshmukh, G., Birwal, P., Datir, R., & Patel, S. (2017). Thermal insulation materials: A tool for energy conservation. *Journal of Food Processing & Technology*, *8*(04), 1-5. doi: 10.4172/2157-7110.1000670

[17] Wheeler, L., Kitinoja, L., & Barrett, D. M. (2015). Use of insulated covers over product crates to reduce losses in amaranth during shipping delays. *Agriculture*, *5*(4), 1204-1223. doi: 10.3390/agriculture5041204

[18] Sharp, A. K., & Irving, A. R. (1981). *Insulating covers for pallets of food*. Scotland: AK, Sharp.

[19] Melis, R. B. (2016). *New techniques and methods for cold chain monitoring and tracking in perishable products*. Doctoral dissertation. Universidad Politécnica de Madrid, Madrid.

[20] Chaiwong, S., & Bishop, C. F. H. (2015). Use of an insulated bag from the supermarket to maintain 'Elsanta' strawberry temperature to households. *Acta Horticulturae*, *1079*, 187–192. doi: 10.17660/ActaHortic.2015.1079

[21] Burgess, G. (1999). Practical thermal resistance and ice requirement calculations for insulating packages. *Packaging Technology and Science: An International Journal*, *12*(2), 75-80.

[22] Harding, K. G. (2018). *Heat Transfer Introduction*. Retrieved September 9, 2021, from https://www.researchgate.net/publication/323144799_Heat_transfer_introduction

[23] Harvey, B. V. (2006). *Mild chilling injury of banana (Cavendish cv. Williams) and its control in the field*. Doctoral dissertation. The University of Adelaide, Adelaide.

[24] Singh, S. P., Burgess, G., & Singh, J. (2008). Performance comparison of thermal insulated packaging boxes, bags and refrigerants for single-parcel shipments. *Packaging Technology and Science: An International Journal*, *21*(1), 25-35. doi: 10.1002/pts.773

CHAPTER 2

LITERATURE REVIEW

2.1 Okra Production

Okra, which is classified to *Abelmoschus esculentus* L. Moench, is an economically important vegetable crop grown in tropical and sub-tropical components of the globe. The local names of okra are different in many parts of the world. It is called 'lady's finger' in England, 'guino-gombo' in Spanish, 'guibeiro' in Portuguese, 'gumbo' in the United States of America and 'bhindi' in India. It is sensitive to frost and greatly low temperature which cause yield loss. An optimum temperature for normal growth and development is between 24 °C to 28 °C [1]. The okra pod is growing quickly after flowering and increases in pod length and diameter occurs during four to six days after pollination. After that, the pods quickly increase in fiber content after 9 days after pollination [2]. The fruits are harvested when immature and eaten as a vegetable. The important nutritions obtained from okra are protein, carbohydrates, minerals, and vitamins, as well as dietary fiber and health-promoting fatty acids [3].

According to the Food and Agriculture Organization Corporate Statistical Database for okra production in 2019, the top ten countries of global production were India, Nigeria, Sudan, Mali, Niger, Pakistan, Cameroon, Ghana, Iraq, and Benin, respectively. India provided the highest production of okra with 6.1 million tones which was accounted for 62% of the total global production [4]. In Thailand, okra is an economic vegetable crop for export. The main planting area is in the central and northern parts of Thailand. The harvesting area of okra has significantly decreased during the five-year period of 2015 to 2019 which were around 70% of the harvested area (rai) in 2015. While the total volume of harvested produces of okra over the 5-year period also decrease around 55% of the harvested produces (tons) (Table 2.1). The largest area for okra cultivation in 2019 year was Suphan Buri (1,816 rai), followed by

Ratburi (547 rai), Nakhon Pathom (357 rai), Kanchanaburi (189 rai), and Phayao (184 rai), respectively [5]. The majority of okra producers in Thailand are contract farmers for export companies, and close collaboration with government expansion agencies provides technological expertise to the farmers. Most of the okra grown in Thailand is exported to other regions. [6].

The export volume of okra has decreased from around 2,500 tons in 2018 to 1,700 tons in 2020 with the value of exported okra around 200 million bath (Table 2.2). The major export markets were Japan, Hong Kong, Switzerland, Germany, and United Arab Emirates, respectively. Japan was the first ranking of imported fresh okra from Thailand with 1,410 tons or around 165 million bath (82.6% of the total exported okra volume) [7].

Table 2.1 Okra Production in Thailand during 2015 to 2019

Year	Harvesting area (rai)	Harvested produces (tons)
2015	11,926.00	10,392.64
2016	10,639.75	5,387.80
2017	7,559.50	6,077.07
2018	4,549.45	3,133.80
2019	3,507.00	4,607.00

Source [5]

Table 2.2 The Exported Fresh Okra from Thailand during 2016 to 2020

Year	Quantity (tons)	Value (million bath)
2016	2,649.4	303.1
2017	2,432.7	276.6
2018	2,532.8	264.0
2019	2,175.7	260.1
2020	1,708.7	200.3

Source [7]

2.2 Postharvest Loss of Okra

Okra suffers from severe postharvest losses particularly under hot tropical conditions, hence it needs a careful handling during and after harvesting and, to minimize losses [8]. As shown in Table 2.3, the loss classification of okra due to quality traits are preharvest and postharvest losses. The main cause of postharvest losses is from mechanical damages, physiological defects, yellowing symptoms and pathological defects [9]. Mechanical damages of okra include compression and bruise damages. Fresh okra is sensitive to bruising. Bruised pods turn to be black or brown color within a few hours [10]. The main symptom from surface injuries, impact and vibration bruises is ridge blackening, which causes membrane disruption, leading to black discoloration along the ribs [11]. Thus, okra harvesting should be handled carefully to avoid bruising [10].

In addition, physiological defects of okra are yellowing and shriveling symptoms. Okra pods lose quality rapidly due to high water loss, becoming yellow, decay and toughen at storage temperature above 25 °C [12]. The packed okra pod in non-ventilated packages caused color fading, and heat build-up due to okra respiration. The ventilated container was suggested for okra packing to avoid the color deterioration [8]. Water loss of okra is very high and causes wilting and shrivelling symptoms (Figure

2.1), which lead to nutritional quality loss [13]. The RH around 95-100% was recommended to reduce dehydration, pod harden and loss of fresh appearance [14]. In term of pathological defect, the major postharvest disease of okra is soft rot (*Rhizopus stolonifera*). The symptom begins with a tiny wet lesion in the injured tissue, which subsequently grows at room temperature, and the whole pod may be coated with a grayish-white mass of mold (Figure 2.2A). Another postharvest disease of okra is pod rot (*Rhizoctonia solani*) which occurs when harvested during the rainy season. The appearance of tiny brown to black dots tightly pressed to the pod surface is a sign of pod rot, which leads to tissue degradation (Figure 2.2B). Therefore, the recommended postharvest techniques to reduce postharvest losses in okra are pre-cooling after harvesting as soon as possible to 10 °C (an optimum temperature), a reduction of wounding on the pod surface by careful handling and avoiding picking [15]. In addition, the effect of temperature and RH on okra quality during storage was described in the section 2.4.

The postharvest losses of okra occur in various stages throughout supply chain management. For example, postharvest loss of okra in sub-Saharan Africa and south Asia was studied and estimated throughout harvesting and marketing chain. The quality losses of okra due to damage and decay was also explored. Losses of okra at farm operation reduced profit around 34% of total profit, followed by loss at retail sold (23.5%) and loss at wholesale (4.5%) [16]. However, the estimation of postharvest losses of okra has been rarely studies in terms of quantitative analysis throughout its supply chain.

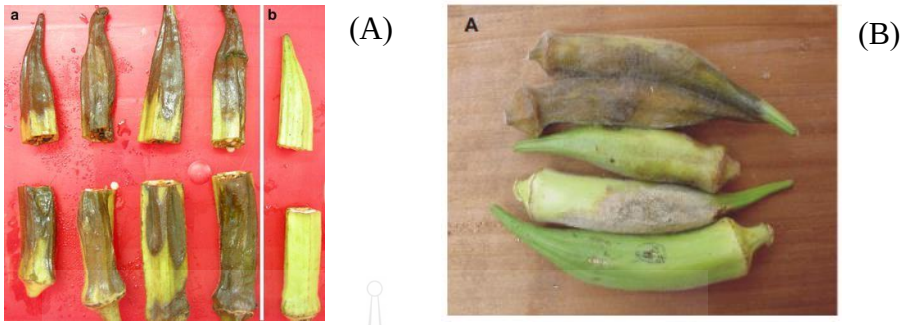
Table 2.3 Main Causes of Pre- and Postharvest Losses in Okra

Preharvest losses	**Postharvest losses**		
	Mechanical damage	**Physiological defects**	**Pathological defects**
Immature	Compression damages	Shriveling	Soft rot
Overmature	Bruises	Yellowing	Wilting
Insect damage	Cuts		Signs of
	Cracks		disease

Source [9]

Source Photographed by the author

Figure 2.1 Shriveling Symptoms in Okra



(A) (B)

Source [17-18]

Figure 2.2 Postharvest Diseases of Okra from Soft Rot (A) and Pod Rot (B)

2.3 Quality and Standard of Okra

The minimum standard requirements of okra quality are fresh, green in color, clean, free of distinct signs of bruising and scratches. For standardization, okra is classified in three classes; class “Extra” is as superior quality. It must be free from any defect. Class I is a slight defect in shape and color. Class II is not qualified for being included in higher classes, but meets minimum requirements specified, for example, firm, fresh, tender, uniform pods with relative straight and green without indication of yellowing [19]. The characteristic pod length is another pod criterion used to define fruit quality. Okra should be harvested every one or two days to ensure that the pods are within the size specification range, due to market criteria for pod length and the rapid rate of growth and development [20].

The maturity and quality are related to the size of okra pod. Okras with bigger pods were found containing higher crude fiber content than those with smaller sized pods [21]. As shown in Table 2.4, the okra standards from Thailand and other organizations or countries (Codex, ASEAN, Philippine, and Kenya) mainly consider pod size for grading. The okra standard for sizing of pod length is different among countries. The okra standards of pod length in Thailand and Philippine are divided into 3 sizes which are size 1 (the largest size of 12-14 cm) and size 3 (the smallest size of

<10 cm). While the Codex and ASEAN standard of okra have 5 or 6 levels of sizing from around 3 cm to 15 cm.

Furthermore, fresh okra with excellent appearance and marketable stages should really be firm, fresh, and tender, with consistent pods that are comparatively straight and green without signs of fading, according to producers and handlers (Figure 2.3) [22]. The rejected appearance and unmarketable stage of okra pods are mainly due to oversized and damaged pods. Okra pods having discoloration, bruising (blackening of the ridges), chemical residue, mechanical injury, deformity, or damage were eliminated during the grading process (Figure 2.4). The decision and satisfaction of consumers on purchasing fresh okra rely on the appearance, quality and food safety [23].

Table 2.4 Okra Standards between Thailand and Other Countries

Country/institute	Sizing (Length of okra pods)	References
Codex	1; 2-4 cm, 5; > 10 cm	World Health Organization [24]
ASEAN	1; > 15 cm, 6; 3-5 cm	Department of Agriculture [25]
Thailand	1; > 12-14 cm, 3; < 10 cm	Ministry of Agriculture and Cooperatives [19]
Philippine	1; > 11.4 cm, 3; < 9 cm	Bureau of product standards [26]
Kenya	The difference in length of the shortest and longest okra in each package shall not exceed 2 cm to 3 cm	Kenya Bureau of Standards [27]

Source [25]

Figure 2.3 Example of Good Appearance and Marketable Stages

Source [25]

Figure 2.4 Example of Rejected Appearance and Unmarketable Stage

2.4 Temperature and Relative Humidity Affecting on Okra Quality

In actuality, the postharvest environment component that has the greatest effect on quality of fresh produce is temperature. Delaying product deterioration is achieved by temperature control. The best preservation of fresh produce quality is only achievable when the produce is cooled to its optimal temperature as soon as possible after harvest. However, in commercial handling during field, transportation, and storage operations, delay in cooling and a poor environmental temperature control, decrease the quality and maximum potential shelf life of fresh produce [28]. Moreover, the RH of surrounding environment should be kept at a level that keeps the water vapor pressure deficit to a minimum [29]. Therefore, the humidity and temperature control are very important for minimizing the differential in water vapor pressure between the product and the environment [28].

2.4.1 Temperature

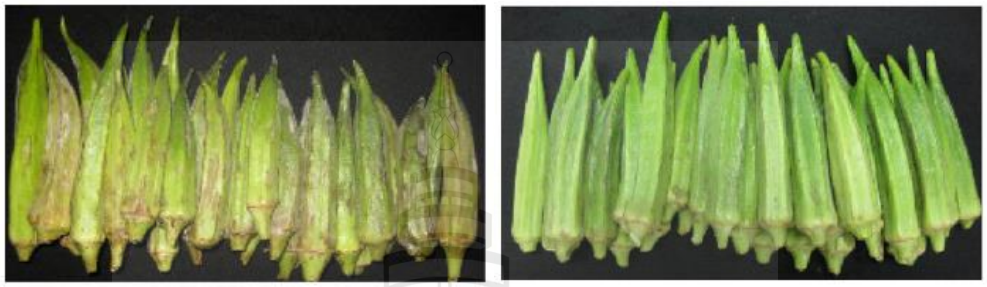
Temperature, as well as RH, are the most important component affecting the shelf life of okra [30]. Okra may be kept successfully for 7 to 10 days at a temperature of 7 to 10 °C. [31]. The storage condition of okra at 4 °C for 5 days maintained the quality of okra [31-32]. However, okra is moderately susceptible to chilling injury when the temperature of storage is below 7 °C [33]. To avoid the development of chilling injury disorder, the storage temperature of okra should be above to 9 °C [34]. The chilling injury incidences are surface pitting, discoloration, and decay occur when the temperature drop to 0 °C may cause severe pitting (Figure 2.5) [31]. The occurrence of severe chilling injury symptom is seen as pitting, water-soaked lesions and surface browning when stored at 4 °C for the storage periods prolonged [35]. Huang et al. mentioned that the okra pods showed chilling injury symptoms such as browning and pitting after 10 days in storage at 7 °C. Loses of okra quality becomes squashy and difficult to eat fresh due to high temperature [36]. The storage condition of okra at 25 °C could maintain the quality of okra around 3 days and after that, it leads into unmarketable [37-39].

Okra can be classified in a high respiration rate plant group [40]. Okra stored at 25-27 °C gave the rate of respiration about 328 to 362 mg CO_2 kg^{-1} h^{-1} while the respiration rate at 5 and 10 °C were 53 to 59 mg CO_2 kg^{-1} h^{-1} and 86 to 95 mg CO_2 kg^{-1} h^{-1}, respectively [31]. These results agree with the Cantwell and Trevor [40] study which reported the respiration rate of okra at 20 °C 232 to 256 mg CO_2 kg^{-1} h^{-1}while the respiration rate at 5 °C and 10 °C were 52 to 58 mg CO_2 kg^{-1} h^{-1} and are 82 to 90 mg CO_2 kg^{-1} h^{-1}, respectively.

Due to significant water loss rates, fresh okra pods have a very limited shelf life [41]. Storage at lower temperature at 5 °C for 5 days reduced weight loss of okra around 10% when compared with those at 10 °C (16%) and 25 °C (27%) [38]. This finding is in agreement with Cheng et al. [37] who reported that the decreasing of okra weight (0.94%) at 4 °C for 5 days was lower than that of storage condition at 25 °C (13.74%). The storage of okra at 25 °C increased weight loss after storage for 5 days due to wilting, yellowing, and decay. Likewise, the result from Rai and Balasubbramanian [42], the decreasing of okra weight (32.2%) was largely influenced by the storage temperature under 34-38 °C for 9 days.

Moreover, okra pod firmness change was investigated at different storage temperature. The firmness of the okra decreased by 36.04% after 5 days of storage at 25 °C while okra firmness reduced by 17.59% after 5 days of storage at 4 °C. The fresh ness of okra as high firmness maintained under cool temperature storage temperature [37]. Moreover, electrolyte leakage is a measurement of the membrane integrity loss due to membrane damage [43]. After storage at 25 °C, the period of storage time affected a gradual increase of the electrolyte leakage from 32.5%, 44.9%, and 67.9%, after storage for 3, 6, and 19 days respectively when compared with that of day 0 [44]. In terms of chlorophyll loss due to high storage temperatures, the chlorophyll content of okra kept at 25 °C for 5 days reduced from 16.32 to 4.54 mg/100g, while the chlorophyll content of okra held at 4 °C was 7.76 mg/100g, indicating low temperature storage-maintained chlorophyll degradation [37]. Similarly, as compared to storage condition at 25 °C (23 mg/100g), the lowest rates of chlorophyll degradation of okra fruits were observed in fruits at 5 or 10 °C (31 mg/100g) after 8 days of storage [38]. Vitamin C content is a main nutritional indicator of okra. After 5 days of storage,

vitamin C content of okra at 4 °C (35.60 mg/100g) was greater than that of okra stored at 25 °C (17.97 mg/100g). Keeping okra at 4 °C successfully prevented vitamin C breakdown and preserved its phytochemicals [37].



Source [36]

Figure 2.5 Chilling Injury Symptom (left) Compared with No Chilling Injury (right) of Okra

2.4.2 Relative Humidity

Only a few researches have investigated an effect of RH on the freshness of fresh produce, and the findings were crucial. The RH of surrounding air is an essential factor, which should be maintained at high level in a cool storage system [28]. RH of 95-100% is suggested for storage of okra to minimize dehydration, pod hardening, and loss of fresh appearance [14]. Environmental RH must be maintained high to avoid a water vapor pressure deficit. As a consequence, whenever RH is too low, transpiration accelerates, causing moisture loss. [29]. Transpiration plays an important role in the loss of immature fruit-type vegetables such as cucumbers, summer squash, eggplant, pepper, okra, and snap bean [11]. By lowering the surface temperature and raising the resistance of the boundary layer, the presence of trichomes on the pod surface of okra may reduce the driving force of transpiration [45]. Transpiration rate is linear and related to VPD, hence loss was reduced by lowering the VPD via reducing air temperature, increasing humidity or creating a barrier to water loss [45-46].

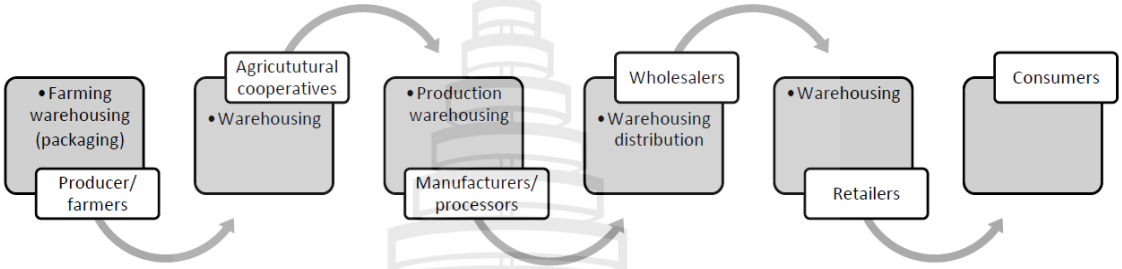
The incidence of rot and berry cracking increased when RH values were approaching saturation (100%) [47]. Excessive weight loss and the development of diseases such as rachis browning and berry drop occurred when RH levels were extremely low [48-49]. This agreement with the findings by Pinto et al. [50] studied the impact of various RH levels during cold storage on table grape postharvest quality. During shelf life, the RH level (90 to 95%) resulted in reduced rot incidence, lower respiration, and better resistance to abscission. RH levels ($\geq$95%) caused berry cracking and RH level ($\leq$90%) increased weight loss and rachis browning. In addition, tamarind pods were stored at 25 °C and 30, 50, 75, and 90% RH for 8 weeks. After of storage, the pods kept at 30 and 50 %RH were found in mold-free, while mold was detected after 8 weeks of storage at 75 %RH and 6 weeks of storage at 90 %RH [51].

Water vapor may accumulate inside the package due to the produce transpiration. The accumulation of water droplets may provide a conducive environment for microbial growth, which leads to sliminess of produce and decay [52-53]. These normally happen when the packing film's water vapor transmission rate does not match the physiological activities of the product [53].

Previous research has examined the impact of temperature and relative humidity on the appearance of fresh produce. The temperature (5, 10, 15, and 22 °C) as well as the RH (76, 86, and 96%) had a considerable impact on the rate of pomegranate fruit transpiration. Storage at 5 °C with 96%RH exhibited the lowest transpiration rate as compared to other storage conditions [54]. For example, in cranberry storage, the experiment was investigated between temperatures ranging from 0 to 10 °C and combined with RH (75% to 98% RH) for 6 months. The results indicated that the RH factor had a greater impact on the commercial appeal of cranberry fruit than the temperature factor [55]. In addition, high RH in cranberry storage increased physiological deterioration. Strawberry at the white tip stage was investigated under RH of 65% and 95%RH and temperatures of 3 and 10 °C. The main cause of strawberry quality reduction was storage temperature. After storage for 12 days, the firmness of strawberry fruit at 10 °C was lower than at 3 °C, but not greatly affected by RH. Weight loss of strawberry at 65% RH, however, was higher than that of at 95% RH [56].

2.5 Supply Chain and Cold Chain Management for Okra

A food supply chain or food system is the process that describes how the food from a farm ends up on table. It entities linking suppliers, manufacturers, freight service providers, retailers, consumers, along with other stakeholders, that take the food from raw material state to the consumer's plates [57-58] (Figure 2.6).



Source [59]

Figure 2.6 Typical Food Supply Chain

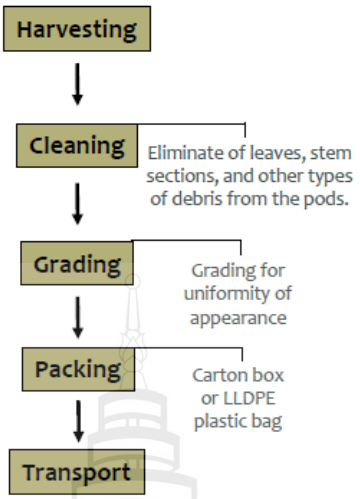
Okra supply chain management includes input producers, traders, manufacturers, and exporters who are engaged in production and selling of the crop [60]. There were three basic routes for the supply of okra; channel 1: The producers contact the buyers on the retail markets (village traders) directly to small-scale consumers; channel 2: On the farm, they sell to middlemen and wholesalers; and channel 3: At the assembly markets, they trade with wholesalers and wholesalers. In India, okra is often picked without any protections in farm to avoid bruising. Okra is harvested and deposited in one location. Growers, packagers, transporters, warehouse owners, and distributors have been involved in the process from harvest to consumption [61]. In Thailand, most farmers for exported okra were small holders and grow okra on their own land. To satisfy the rising demand from Japanese market, local Thai export companies have established a network of contract growers in the western and central parts of the country [6].

Regarding to postharvest handling of okra in supply chain, a typical postharvest handling of okra includes; harvesting, cleaning, grading, packing and transport (Figure 2.7). At harvesting, the okra pods with the length of 7.5 to 12.5 cm or around 4 to 6 days after flowering should be harvested, using hand harvesting with clippers. During harvesting, all containers in postharvest operation should be ventilated and shallow. In addition, the harvested okra should be graded in the field. After harvesting, okra pods should be transferred to plastic crates for transport to the packing house. A light-colored material should be used for covering container to minimize absorption or radiation from sunlight and also limit heat build-up. Grading and packing an okra pods on the same day of harvest prevent overheating and avoid bacterial soft rot infection. Package must be filled properly to avoid bruising caused by over filling. Filling in package (random packing) causes pod damage due to pods can be bruised by moving around inside the package during handling and transportation [15].

The postharvest handling for exported okra depends on the operation. In India, a postharvest procedure of okra for export market, in terms of harvesting and packing, the regular and minimal handlings of okra were compared. Pods were harvested by hand, collected in gunny sacks (20 kg), and then transported to corrugated fiberboard (CFB) boxes (2.0 kg) for regular handling. While a minimum handling technique involved with harvesting using a clipper, wearing cotton gloves and field packing in CFB boxes. The results showed that the minimum handling of okra by picking and field packaging in CFB boxes maintained freshness, firmness, and quality of okra up to 13 days at 8 °C without any chemical treatment. While the normal handling turned completely black and rotten after 9 days of storage. However, studies on postharvest handling of okra are still very limited in South East Asia, especially in Thailand. Until recently, there has been no study in postharvest handling of okra in Thailand with respect to the improvement of handling system to reduce loss and maintain quality.

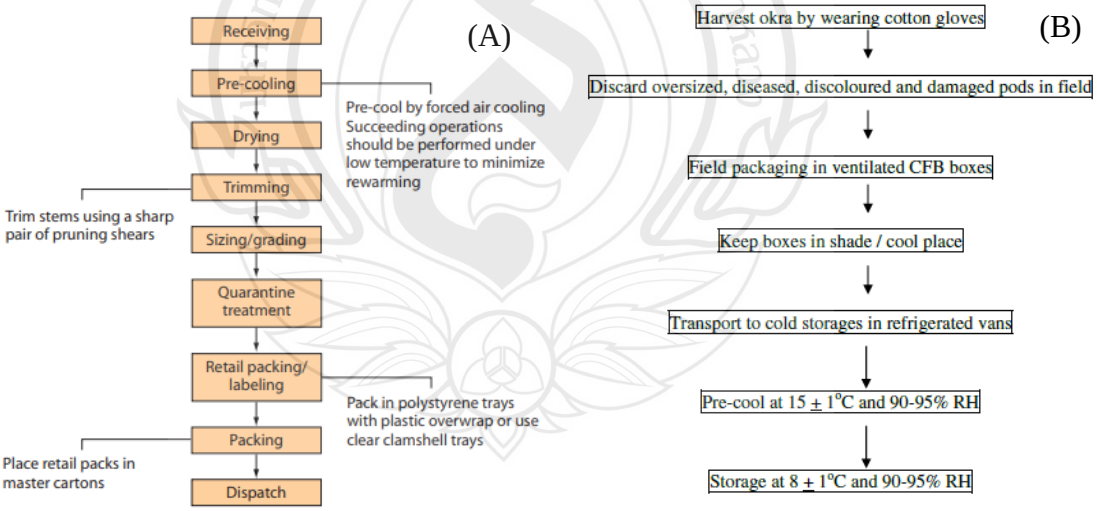
The packing-house system for many commodities across Asia and the Pacific region was investigated. The flow chart for packinghouse operation was developed for export markets. The process flow for okra were different from typical handling such that a forced-air cooling has been used [62], similar to the handling for exported okra in India [61] (Figure 2.8A and B). A cooling step is a part of cool chain management.

The operation of fresh produce from producing area to customer through various storage and transport intermediates without any significant change in storage temperature and RH is known as the cool chain [63]. The continuous exposure of the product to proper air temperature and RH is essential for effective cool chain [64]. The cool chain management of okra was reported only in cooling and storage stages [31, 32, 38, 42, 44, 65]. For cooling step, forced-air cooling was employed for exported okra after receiving from field [62]. In India, room cooling at 15 °C was used for cooling exported okra before storage at 8 °C [61]. However, very few researches have reported the cooling condition and efficiency of both room and forced-air cooling to reduce okra temperature and extend storage life or shelf-life. For example, a comparison between forced-air cooling and hydrocooling was investigated in the postharvest quality of okra. The results showed that okra pods from forced-air cooled had better appearance than those of hydrocooling after storage at 10 °C for 7 days. The okra in vented clamshell containers with forced-air cooling had acceptable appearance, more tender and less weight loss after storage condition [65]. Interestingly, most studies in cool chain management of okra have been focused on temperature storage. There have been few studies in cooling condition and the effect of cooling on quality of okra. Although some research has been carried out on cooling and cool storage, no study has reported on cool chain management of okra throughout its supply chain.



Source [15]

Figure 2.7 Typical Postharvest Handling of Okra



Source [61-62]

Figure 2.8 Postharvest Handling of Okra for the Export Market

2.6 Pallet Covers Materials

To guarantee product integrity, many commercial businesses concentrate their product transportation on the batch (pallet) level, which frequently proves to be the most commercially timely and economically feasible option [66]. Pallet covers materials are mostly used in commercial practices for covering fresh produce during transportation. These coverings are intended to assist maintaining the humidity within the pallets by attenuating rapid temperature fluctuations. They are made up of an insulating substance that is applied to the pallet after it has been constructed. It must be placed when the temperature and humidity are at their ideal levels so that the cover may maintain them for as long as feasible [67].

Low thermal conductivity is used as insulating materials to limit heat transmission, but radiation and convection also play roles [68]. The thermal conductivity of most materials decreases with an increasing temperature. By replacing the gas in cellular structure, absorbed moisture is known to reduce the thermal performance of cellular polymers, depending on the temperature from either side of the insulation. Latent heat transfer may also occur as a consequence of evaporation and condensation [69]. In this section, the most common insulating materials used for pallet cover applications including thermal insulation material, aluminium foil, and nonwoven fabrics were explained in term of material, thermal conductivity. As shown in Table 2.5, thermal conductivity is different in each material, thermal-insulated material including polystyrene foam and polyurethane have the lowest in thermal conductivity as a mean of constraining the heat transfer and followed by polypropylene. Aluminum foil is one kind of reflective insulation material that has a high thermal conductivity and reflects heat to effectively reduce heat radiation [70].

Table 2.5 Thermal Conductivity at 20 °C for Different Materials

Material	Thermal conductivity (W m^{-1} K^{-1})
Thermal insulation material	
• Polystyrene foam	0.03 – 0.04
• Polyurethane	0.02 – 0.03
Aluminum	237 (pure)
	120 – 180 (alloys)
Nonwoven fabrics (polypropylene (PP))	0.25

Source [71]

2.6.1 Thermal Insulation Materials

The material for thermal insulation is described as a substance or mixture of materials that delay thermal flow and are adaptable to any shape, structure and surface [72]. Insulating materials are used to thermally isolate the system and significantly decrease the heat transfer rate between the system and the surrounding area or environment [73]. Thermal insulation materials are particularly developed to decrease thermal flow by reducing thermal convection, radiation, and conduction, while performing one or more of the following functions; energy conservation by reducing thermal loss or gain, regulation of the surface for individual safety and convenience, and enabling process vapor flow and water condensation [74]. Thermal insulation materials may be classified into one of three basic material categories. Fibrous insulation is made up of fine diameter fibers that delicately partition the material's air space. Small individual cells are isolated from one another in cellular insulations. Glass or foamed plastics such as polystyrene (closed cell), polyurethane, polyisocyanurate, polyolefin, or elastomer may be used as the cellular material. Small nodules in granular insulations include voids or hollows. Because gas may pass between the separate gaps, these materials are not regarded as genuine cellular materials. This kind may be made into a loose or pourable substance or as a rigid insulation with the addition of a binder

and fibers [75]. Polystyrene is normally used for pallet cover material in combine with other material such as aluminum foil or coat with polyurethane for cover fresh produce during transportation (Figure 2.10).

Source [76]

Figure 2.9 Polystyrene

2.6.2 Aluminum Foil

Aluminum foil is a reflective insulation material, which consists of one or more low-emittance surfaces and can reflect heat back out, thus reducing heat radiation effectively [70]. Aluminum foil has very little radiation coefficient and good ability of antiradiation, which can effectively reduce thermal radiation [77]. Since 1950s, aluminum foil has shown excellent performance, in many countries in Europe and America, being used in the building and industrial as thermal insulation materials [78]. However, in the pallet cover, aluminum foil was used as one layer of covering material, in combined with other material such as white foam for covered fresh produce during delay shipping [79] (Figure 2.11).

Source [80]

Figure 2.10 Aluminum Foil

2.6.3 Nonwovens

Spun bond nonwovens are made by a combined processes of fiber spinning, fiber depositing, web binding, and winding to create rolls [81] (Figure 2.12). Nonwovens may be produced from webs that are set out in various ways, such as horizontal, transverse, or randomly, and bound together using adhesive or thermoplastic fibers that are heated [82]. Nonwovens were tested for their flexural stiffness, which is also referred to as bending rigidity. To estimate the bending stiffness of nonwoven fabrics, one assumes they are made up of unit cells and computes the bending moment divided by the radius of curvature of a cell area [83]. Nonwovens are useful in a variety of applications, including transportation, construction management, manufacturing, and, more recently, agricultural [84]. In agricultural area, the application of nonwoven was developed for various applications such as crop cover, frost protection, landscape fabric, green house shading, and insect protection, and also be used to reduce extreme temperature differences [85].

Source [86]

Figure 2.11 Nonwoven Fabric

2.7 Pallet Covers for Fresh Produce

Pallet cover is an alternative method that has been used as a technological packaging to reduce waste from food spoilage by reducing temperature and humidity change during transportation [66]. The use of insulated pallet covers could decrease the temperature fluctuation during transportation by either a refrigerated vehicle or in a shaded area without any refrigerated dock [87]. Similar observation was made by Bollen et al. [88] in individual pallet of air transported produce. The combinations of an insulated pallet covering and a supplemental coolant were investigated, using asparagus pallets. The use of insulated pallet wraps in term of disposal of air exchange gave the most benefit for the reduction rate of temperature fluctuation. In section, the pallet cover application for fresh produce in both academic research and commercial use in postharvest handling was explained.

2.7.1 Pallet Covers for Fresh Produce in Academic Research

From previous studies reported on pallet cover, there has been a few numbers of published work describing the beneficial effect of pallet cover on reducing postharvest losses for fresh produce (Table 2.6). The pallet covering on sides and bottom with insulated pallet cover (Reflectix™) in amaranth could reduce weight loss

and wilting, and preserve a desirable dark green color. In addition, the use of pallet cover gave high score in overall quality and better than the uncovered [79]. Similarly, study by Chaiwong and Bishop [89] on the light weight insulated bag showed that insulated bag was a possible to serve for a cool temperatu9e management and reduce strawberry breakdown of cool chain from supermarket to domestic refrigerator. For other application of pallet cover, in fumigation of lettuce, the use of double-bubble foil insulation cover could be used to keep pre-chilled lettuce at low temperature and was suitable for low-temperature phosphine fumigation to control western flower thrips on harvested lettuce [90]. Recently, Melis (2016) [66] reported the covering with insulated pallet covers showed better temperature preservation than that with no cover and temperature changes occurred slower than with no cover in chard, cucumber, and carrot.

Table 2.6 Pallet Cover for Fresh Produce in Academic Research

Commodities	**Materials**	**Results**	**References**
Lettuce	Double-bubble foil insulation cover	Cover reduced the effect of changes in ambient temperature on lettuce temperature profiles during phosphine fumigation treatments.	Liu [90]
Amaranth	Reflectix™ insulation material (Aluminum foil/0.8cm polyrthylene/bubble pack) for pallet cover compared with no cover	Improved overall quality and reduced weight loss.	Wheeler et al. [79]

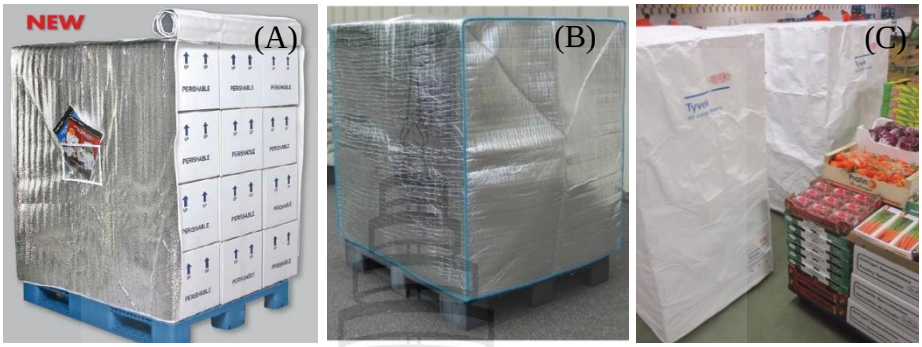
Table 2.6 (continued)

Commodities	Materials	Results	References
Strawberries	Light weight insulated bags; nonwoven material made from HDPE	Kept cool strawberries and delayed the increase of air and pulp temperatures	Chaiwong and Bishop [89]
Chard, cucumber, carrots	Tyvek®, Metalized PET, Metalized PET bubbles and no cover as control	The covering with insulated pallet covers showed the temperature preservation better than no cover. Temperature fluctuations were slower than before there was no cover.	Melis [66]

2.7.2 Pallet Covers for Fresh Produce in Commercial Practices

The pallet cover has been used variously in commercial practices by using different cover materials (Table 2.7). Polystyrene is normally used as thermal insulation material for pallet cover in combined with other material such as aluminum foil (a reflective insulation), coated with polyurethane for covering fresh produce during transportation [91]. The commercial brands of pallet cover are including; ICE-BRIX® brand, Reflectix™ brand. WEICO® brand, TempShield, Kodiakooler®, and ISO KIT. Nonwoven fabrics under a brand of Tyvek® from Dupont is used in cargo cover material for perishable products including fruits, vegetables, cut flower during air transportation. Materials for pallet cover are of many types, which depend on production line. Combination of nylon, polyurethane coated, and polyester fibrefill were used as thermal insulation cover in the Raindall® brand for floral, food, and beverage transportation. Various types of pallet cover in commercial practice are shown in Figure 2.13. In addition, the insulated package was used in a small scale for primary

packaging (individual package). For example, Chill buddy™ had some various applications such as retail pods, pallet shroud, and insulated bag for fresh produce transportation.



Source [92-94]

Figure 2.12 Pallet Cover in Commercial Practices Including ICE-BRIX® (A), WEICO® (B), and Tyvek® (C)

Table 2.7 Pallet Cover for Fresh Produce in Commercial Practices

Commodities	Properties	References
Perishable crops and cut flower	Nonwoven with white color. Breathable cover with good O_2 transmission and high water vapour permeability.	Tyvek®, DuPont
Food products	Seven layers; two layers of aluminum each bonded to a tough layer of polyethylene for strength; two inner layers of bubble	TempShield
Fresh fruits and vegetables	Polyester fiberfill and polyurethane coating	Randall manufacturing

Table 2.7 (continued)

Commodities	Properties	References
Fresh produce	Seven layers; Alu/PE/Aerogel/woven fabric/PA/Alu/PET	WEICO®
Food and fresh produce	Aluminum exterior and 4 mm white foam interior	ICE-BRIX®
Fresh produce	Aluminum with white foam	Reflectix™

2.8 Thermal Insulation Material Testing

For determination of thermal insulation property, the material under test is kept within an appropriate temperature range, which is monitored for any adjustments, then exposed to different environmental conditions to evaluate the material's efficiency [95].

Generally, the thermal characteristics of insulating materials are well recognized or can be tested with accuracy. It is possible to determine the quantity of heat transfer through any combination of materials. The knowledge and understanding of specific technical terms; however, is required in order to calculate heat losses and comprehend many variables that are involved, including heat transfer and thermal resistance (R-value) [96]. A good insulating material should have a variety of properties, depending on the application, to enhanced resistance and heat transfer [68]. Permeance to water vapor is another insulating material property. Although protecting the insulation against moisture gain is a primary concern, appropriate design of water vapor barriers for insulation material is also essential [97].

2.8.1 Heat Transfer

The process of energy flow caused by a temperature difference is known as heat transfer [71]. Passive thermal protection systems use three kinds of heat transfer: conduction, convection, and radiation [71, 98]. Conduction is a kind of heat that occurs

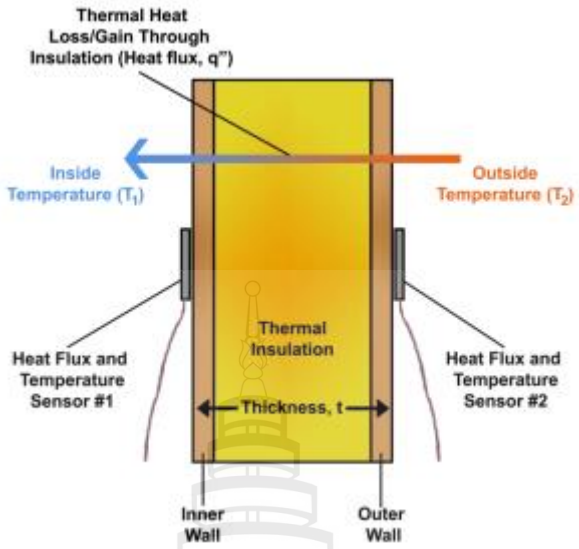
as a result of direct contact without the movement of a material, with energy flowing from a hotter to a cooler portion. Convection is a kind of heat transmission that occurs when molecules in a fluid move around. Radiation is a kind of energy transfer that occurs when electrons and protons in a substance move owing to electromagnetic waves [71]. Each of them has a significant impact on how heat is absorbed in a pallet load [71, 98]. When conducting thermal insulation material testing for temperature protection, it is also essential to understand heat transmission [66]. The heat transfer calculations are accounted in calculating the ultimate temperatures of materials and the time it takes for these materials to achieve these temperatures, as well as determining the amount of insulation needed to guarantee heat is not lost from a system [71, 98].

For thermal insulation applications, the insulation capacity of materials is determined by their layer thickness (conduction), number of surfaces (convection), and number of reflecting surfaces such as aluminum foil (radiation) [99]. Insulation materials with low thermal conductivity is usually used to limit heat transmission, but radiation and convection are also important [68]. The thermal conductivity of most materials diminishes as the temperature rises.

2.8.2 R-value Measurement

R-value measurement is a measure of how well a two-dimensional barrier resists heat conductive energy passing through it [100]. The R-value is defined as the temperature difference per unit of heat flux needed to sustain one unit of heat flow between the warmer and cooler surfaces of a barrier. The R-value is most likely the constant value when there is no change in heat flow between the warmer and cooler sides. It is often expressed in the form of R-value per unit length in the case of materials (e.g., per inch or metre of thickness). R-values are increased for layers of materials for improving higher R-value and better performance [101].

A few simple measurements made available by heat flux sensors may be used to estimate the R-value of thermal insulation. Figure 2.9 is a diagram showing heat transmission through a building wall. Measurements should be performed over a long period of time and analysed to establish the material's total effective R-value [102].



Source [103]

Figure 2.13 Diagram of Conductive Heat Flow Through a Material and the Necessary Experimental Setup to Determine R-value of the Material

2.8.3 Water Vapor Permeability (WVP)

The thermal comfort characteristics of material systems are significantly influenced by the water vapor transport properties of materials [104]. The diffusion equation of the vapor is used to determine WVP of materials. Measurements are typically done in an environment that is maintained at constant temperature. Two environments with different RH are separated by a test specimen of known area and thickness. The rate of vapor flow over the specimen is then gravimetrically measured under steady-state conditions [105].

Once the steady state is reached, WVP describes a material's ability to transfer moisture under a vapour differential pressure. Vapour permeability involves (a) diffusion (transport of water molecules by contact with each other), (b) effusion (transport of water molecules by impact with the walls of pores), and (c) liquid transfer (associated with condensation) [106]. In addition, WVP should be extremely low in the best insulating materials [68].

References

[1] Tripathi, K. K., Warrier, R., Govila, O. P., & Ahuja, V. (2011). *Biology of Abelmoschus esculentus L. (okra)*. Retrieved September 11, 2021, from https://biosafety.icar.gov.in/wp- content/uploads/2015/11/Biology_of_ Okra1.pdf

[2] Barnwal, A. K., Pal, A. K., Tiwari, A., Pal, S., & Singh, A. K. (2017). Effect of picking stages on fruit and seed development in okra [*Abelmoschus esculentus* (L.) Moench] Cultivars Kashi Pragati and Kashi Kranti. *International Journal of Agriculture, Environment and Biotechnology, 10*(6), 695-702. doi: 10.5958/2230-732X.2017.00086.9

[3] Gemede, H. F., Ratta, N., Haki, G. D., Woldegiorgis, A. Z., & Beyene, F. (2015). Nutritional quality and health benefits of okra (*Abelmoschus esculentus*): A review. *International Journal of Nutrition and Food Sciences*, *6*(458), 2.

[4] FAOSTAT. (2019). *Food and Agriculture Organization (FAO), Statistical Data. 2019*. Retrieved July 10, 2020, from http://www.fao.org/faostat/en/#data/QC

[5] Agricultural production information system. (2019). *Office of Agricultural Economics, Statistic data. 2019*. Retrieved July 6, 2020, from http://www. oae.go.th/view/1/Information/EN-US

[6] Tattanakorn, M., & Kumar, P. (2004). *Baseline survey export okra production in Thailand*. Retrieved August 6, 2020, from https://www.yumpu.com/en/ document/read/38739985/baseline-survey-export-okra-production-in-thailand

[7] Thai Custom. (2020). *Statistic report 2020*. Retrieved April 14, 2021, from http://www.customs.go.th/statistic_report.php?lang=en&tariff_code=07099990003

[8] Medlicot, A. (1990). *Postharvest handling of okra: Product specifications and postharvest handling for fruits, vegetables and root crops exported from the Caribbean*. Ottawa: Fintrac.

[9] Flores, E., Dela Cruz, R., & Antolin, M. C. (2018). Postharvest handling systems and losses of eggplant in major producing areas of the Philippines. *Asian Journal of Postharvest and Mechanization*, *46*, 116-133.

[10] Moretti, C. L., Sargents, S. A., Huber, D. J., Gablbo, A. G., & Puschmann, R. (1998). Chemical composition and properties of pericarp, locule, and placental tissues of tomatoes with internal bruising. *A Journal of the American Society for Horticultural Science*, *123*, 656-600. doi: 10.21273/JASHS.123.4.65

[11] Kader, A. A. (1983). Postharvest quality maintenance of fruits and vegetables in developing countries. In M. Lieberman (Ed.), *Postharvest Physiology and Crop Preservation* (pp. 455-570). New York: Plenum Publishing Corporation.

[12] Salunkhe, D. K., & Desai, B. B. (1984). *Postharvest biotechnology of fruits* (Vol.1). Florida: CRC Press.

[13] Thompson, A. K. (1996). *Postharvest technology of fruits and vegetables*. New Jersey: Hartnolls Ltd. Bodmin Cornwell.

[14] Ngure, J. W., Aguyoh, J. N., & Gaoquiong, L. (2009). Interactive effects of packaging and storage temperatures on the shelf-life of okra. *ARPN Journal of Agricultural and Biological Science*, *4*(3), 43-52.

[15] New Guyana Marketing Corporation. (2003). *Publications in the postharvest handling technical bulletin series. Okra: Postharvest Care and Market Preparation*. Retrieved September 14, 2021, from http://agriculture.gov.gy/wp-content/uploads/2016/01/Okra.pdf

[16] Kitinoja, L., & AlHassan, H. Y. (2012). Identification of appropriate postharvest technologies for small scale horticultural farmers and marketers in Sub-Saharan Africa and South Asia-Part 1. Postharvest losses and quality assessments. *Acta Horticulturae*, *934*, 31-40. doi: 10.17660/ActaHortic.2012.934.1

[17] Nazerian, E., Sijam, K., Meor Ahmad, Z., & Keshavarz, K. (2011). Characterization of Pectobacterium carotovorum causing a new soft rot disease on okra in Malaysia. *Journal of General Plant Pathology*, *77*, 292–294.

[18] Henz, G. P., Lopes, C. A., & Reis, A. (2007). A novel postharvest rot of okra pods caused by *Rhizoctonia solani* in Brazil. *Fitopatologia Brasileira*, *32*(3), 237-240. doi: 10.1590/S0100-41582007000300008

[19] Ministry of Agriculture and Cooperatives. (2004). *Thai Agriculture Standard: Okra (TAS 1501-2004).* Retrieved October 14, 2020, from https://www.acfs.go.th/standard/download/eng/okra.pdf

[20] Diaz, F. A., Ortegon, M. A. S., & Loera, G. J. (1997). Fruit characteristics and yield of new okra hybrids. *Subtropical Plant Science*, *49*, 8-11.

[21] Kalra, C. L., Raina, B. L., Teotia, M. S., & Pruthi, J. S. (1983). The influence of varieties on the quality of dehydrated okra (*Hibiscus esculentus* L). *Indian Food Packer*, *37*(6), 47-55.

[22] Sanders, D. (2001). Okra production. In *Horticulture Information Leaflet 8019*. North Carolina: North Carolina State University.

[23] Sadílek, T. (2019). Perception of food quality by consumers: Literature review. *European Research Studies*, *22*(1), 57-67.

[24] World Health Organization. (2014). *International food standard: Standard for okra (CODEX STAN 318-2014)*. Retrieved October 14, 2020, from https://www.fao.org/input/download/standards/13806/CXS_318e_2014.pdf

[25] ASEAN Ministers Meeting on Agriculture and Forestry (AMAF). (2011). *ASEAN standard for okra (ASEAN Stan 22:2011)*. Retrieved October 14, 2020, from https://docplayer.net/174594184-Asean-standard-for-okra-asean-stan-22-2011.html

[26] Bureau of product standards. (2008). *Philippine national standard for okra (PNS/BAFPS 39:2008)*. Retrieved October 14, 2020, from http://www.bafs.da.gov.ph/bafs_admin/admin_page/pns_file/2021-02-24-PNS-BAFPS%2039-2008%20-%20Okra.pdf

[27] Kenya Bureau of Standards. (2016). *Kenya standard; Fresh okra- Specification (KS 787: 2016 ICS 67.080)*. Retrieved October 14, 2020, from https://members.wto.org/crnattachments/2017/TBT/KEN/17_0353_00_e.pdf

[28] do Nascimento Nunes, M. C. (2008). Impact of environmental conditions on fruit and vegetable quality. *Stewart Postharvest Review, 4*(4), 1-14. doi: 10.2212/spr.2008.4.4

[29] Alférez, F., & Burns, J. K. (2004). Postharvest peel pitting at non-chilling temperatures in grapefruit is promoted by changes from low to high relative humidity during storage. *Postharvest Biology and Technology, 32*(1), 79-87. doi: 10.1016/j.postharvbio.2003.09.018

[30] Abdul Hadi, A. M., Matlob, A. N., & Yousef, Y. H. (1989). *Handling and storage of fruits and vegetables*. Iraq: University of Baghdad.

[31] Hardenburg, R. E., Watada, A. E., & Wang, C. Y. (1986). The commercial storage of fruits. In *Vegetables and Florist and Nursery stocks* (Vol. 66). Washington: United States Department of Agriculture.

[32] Cheng, Z., Gong, X., Jing, W., Peng, Z., & Li, J. (2018). Quality change of postharvest okra at different storage temperatures. *Journal of Food Engineering and Technology, 7*(1), 43-43.

[33] Perkins-Veazie, P., & Collins, J. K. (1992). Cultivar, packing and storage temperature differences in postharvest shelf life of okra. *HortTechnology, 2*, 350-352. doi: 10.21273/HORTTECH.2.3.350

[34] Lyons, J. M., & Breidenbach, R. W. (1987). Chilling injury. In J. Weichmann (Ed.), *Postharvest physiology of vegetables* (pp. 305-326). New York: Marcel Dekker.

[35] Wang, C. Y. (2000). Postharvest techniques for reducing low temperature injury in chilling sensitive commodities. In F. Artes, M. I. Gil, & M. A. Conesa (Eds.), *Improving postharvest technologies of fruits vegetables and ornamentals.* Paris: International Institute of Refrigeration.

[36] Huang, S., Li, T., Jiang, G., Xie, W., . . . Duan, X. (2012). 1-Methylcyclopropene reduces chilling injury of harvested okra (*Hibiscus esculentus L*.) pod. *Scientia Horticulturae, 141*, 42-46. doi: 10.1016/j.scienta.2012.04.016

[37] Cheng, Z., Gong, X., Jing, W., Peng, Z., & Li, J. (2018). Quality change of postharvest okra at different storage temperatures. *Journal of Food Engineering and Technology, 7*(1), 43-43. doi: 10.32732/jfet

[38] Finger, F. L., Della-Justina, M. E., Casali, V. W. D., & Puiatti, M. (2008). Temperature and modified atmosphere affect the quality of okra. *Scientia Agricola, 65*, 360-364.

[39] Babarinde, G. O., & Fabunmi, O. A. (2009). Effects of packaging materials and storage temperature on quality of fresh okra (*Abelmoschus esculentus*) fruit. *Journal of Agriculture and Rural Development in the Tropics and Subtropics, 42*, 151-156.

[40] Cantwell, M., & Trevor, S. (2002). *Recommendations for maintaining postharvest Quality*. California: University of California, Davis.

[41] Tamura, J., & Minamide, T. (1984). Harvesting maturity, handling, and storage of okra pods. *Bulletin of the University of Osaka Prefecture, 36*, 87-97.

[42] Rai, D. R., & Balasubramanian, S. (2009). Qualitative and textural changes in fresh okra pods (*Hibiscus esculentus* L.) under modified atmosphere packaging in perforated film packages. *Food Science and Technology International, 15*(2), 131-138. doi: 10.1177/1082013208106206

[43] Borsos-Matovina, V., & Blake, T. J. (2001). Seed treatment with the antioxidant Ambiol enhances membrane protection in seedlings exposed to drought and low temperatures. *Trees, 15*, 163–167.

[44] Liu, J., Yuan, Y., Wu, Q., Zhao, Y., . . . Yang, B. (2017). Analyses of quality and metabolites levels of okra during postharvest senescence by 1H-high resolution NMR. *Postharvest Biology and Technology, 132*, 171-178. doi: 10.1016/j.postharvbio.2017.07.002

[45] Ben-Yehoshua, S., & Rodov, V. (2002). Transpiration and water stress. In *Postharvest physiology and pathology of vegetables* (pp. 143-197). Florida: CRC Press.

[46] Grierson, W., & Wardowski, W. F. (1978). Relative humidity effects on the postharvest life of fruits and vegetables. *HortScience, 13*, 570-574.

[47] Schwarz, A. (1994). Relative humidity in cool stores; Measurement, control and influence of discreet factors. *Acta Horticulturae, 368*, 684-692. doi: 10.17660 /ActaHortic.1994.368.82

[48] Brackmann, A., Mazaro, S. M., & Waclawovsky, A. J. (2000). Armazenamento refrigerado de uvas cvs. Tardia de Caxias e Dona Zilá. *Ciência Rural, 30*, 581-586.

[49] Crisosto, C. H. J. L., Smilanick, J., & Dokoozlian, N. (2001). Table grapes suffer water loss, stem browning during cooling delays. *California Agriculture, 55*(1), 39-42.

[50] Pinto, J. A. V., Schorr, M. R. W., Thewes, F. R., Ceconi, D. L., . . . Fronza, D. (2015). Relative humidity during cold storage on postharvest quality of 'Niagara Rosada' table grapes. *Ciência Rural, 45*, 386-391. doi: 10.1590/ 0103-8478cr20130307

[51] Nattaporn, J., & Krittika, T. (2010). Effect of storage time and relative humidity on transportability of sweet tamarind. *Acta Horticulturae, 875*, 151-156. doi: 10.17660/ActaHortic.2010.875.18

[52] Song, Y., Vorsa, N., & Yam, K. L. (2002). Modeling respiration–transpiration in a modified atmosphere packaging system containing blueberry. *Journal of Food Engineering, 53*(2), 103-109. doi: 10.1016/S0260-8774(01)00146-7

[53] Caleb, O. J., Mahajan, P. V., Al-Said, F. A., & Opara, U. L. (2013). Transpiration rate and quality of pomegranate arils as affected by storage conditions. *CyTA-Journal of Food, 11*(3), 199-207. doi: 10.1080/19476337.2012.72180

[54] Aindongo, W. V., Caleb, O. J., Mahajan, P. V., Manley, M., & Opara, U. L. (2014). Effects of storage conditions on transpiration rate of pomegranate aril-sacs and arils. *South African Journal of Plant and Soil, 31*(1), 7-11. doi: 10.1080/02571862.2014.868049

[55] Forney, C. F. (2008). Optimizing the storage temperature and humidity for fresh cranberries: A reassessment of chilling sensitivity. *HortScience, 43*(2), 439-446. doi: 10.21273/HORTSCI.43.2.439

[56] Shin, Y., Ryu, J. A., Liu, R. H., Nock, J. F., & Watkins, C. B. (2008). Harvest maturity, storage temperature and relative humidity affect fruit quality, antioxidant contents and activity, and inhibition of cell proliferation of strawberry fruit. *Postharvest Biology and Technology, 49*(2), 201-209. doi: 10.1016/j.postharvbio.2008.02.008

[57] Dani, S. (2015). *Food supply chain management and logistics: From farm to fork*. London: Kogan Page Publishers.

[58] Nagurney, A., & Li, D. (2016). *Competing on supply chain quality*. New York: Springer International Publishing.

[59] Iakovou, E., Bochtis, D., Vlachos, D., & Aidonis, D. (2016). *Supply chain management for sustainable food networks*. New York: John Wiley & Sons.

[60] Islam, M. S., Faruq, A. N., Chowdhury, M. M. H., Shahjahan, M., & Kabir, K. (2015). Value chain analysis of exportable okra (*Abelmoschus esculentus L.*) from Bangladesh. *The Agriculturists*, *13*(1), 133-139. doi: 10.3329/agric.v13i1.26557

[61] Dhall, R. K., Sharma, S. R., & Mahajan, B. V. C. (2014). Development of post-harvest protocol of okra for export marketing. *Journal of Food Science and Technology*, *51*(8), 1622-1625.

[62] Food and Agriculture Organization. (2012). *Good practice in the design management and operation of a fresh produce packing-house*. Retrieved September 9, 2021, from https://www.fao.org/3/i2678e/i2678e00.pdf

[63] Dodd, M. C. (2013). *Identifying and rectifying temperature and humidity abuse in various fruit supply chains from South Africa to the United Kingdom*. World Cold Chain Conference on 22-23 May 2013, Impact Convention Centre, Bangkok, Thailand.

[64] Florkowski, W. J., Prussia, S. E., Shewfelt, R. L., & Brueckner, B., (2009). *Postharvest Handling: A Systems Approach* (2nd ed.). Massachusetts: Academic Press.

[65] Sargent, S. A., Fox, A. J., Coelho, E. C. M., & Locascio, S. J. (1996). Comparison of Cooling and Packaging Methods to Extend the Postharvest Life of Okra. In *Proceeding- Florida state horticultural society* (Vol. 109, pp. 285-290). Florida: Florida state horticultural society.

[66] Melis, R. B. (2016). *New techniques and methods for cold chain monitoring and tracking in perishable products*. Doctoral dissertation. Universidad Politécnica de Madrid, Madrid.

[67] Pelletier, W., Brecht, J. K., do Nascimento Nunes, M. C., & Émond, J. P. (2011). Quality of strawberries shipped by truck from California to Florida as fluenced by postharvest temperature management practices. *HortTechnology*, *21*, 482–493.

[68] Singh, S. P., Burgess, G., & Singh, J. (2008). Performance comparison of thermal insulated packaging boxes, bags and refrigerants for single-parcel shipments. *Packaging Technology and Science: An International Journal*, *21*(1), 25-35. doi: 10.1002/pts.773

[69] Desjarlais, A. O., & Zarr, R. R. (Eds.). (2002). *Insulation materials, testing and applications* (Vol. 1426). Pennsylvania: ASTM International.

[70] Wang, W., & Guan, S. (2017). *Study on fabrication and properties of the aluminium foil*. Retrieved July 2, 2020, from http://iccmcentral.org/Proceedings/ICCM21proceedings/papers/4353.pdf

[71] Harding, K. G. (2018). *Heat Transfer Introduction*. Retrieved September 9, 2021, from https://www.researchgate.net/publication/323144799_Heat_transfer_introduction

[72] *Thermal insulation materials, technical characteristics and selection criteria*. (n.d.). Retrieved November 11, 2021, from https://www.fao.org/3/Y5013E/y5013e08.htm

[73] Deshmukh, G., Birwal, P., Datir, R., & Patel, S. (2017). Thermal insulation materials: A tool for energy conservation. *Journal of Food Processing & Technology, 8*(04), 1-5. doi: 10.4172/2157-7110.1000670

[74] Khandelwal, M. (2010). *Basics about insulations*. Gujarat: Nirma industries.

[75] The Thermal Insulation Association of Southern Africa (TIASA). (2001). *Thermal insulation handbook*. Retrieved November 11, 2021, from https://www.aaamsa.co.za/docs_new/TIASA/Handbook_Chapter1.pdf

[76] *History of the world in 52 packs 20: Polystyrene*. (2015). Retrieved September 8, 2021, from https://www.packagingnews.co.uk/features/comment/history-of-the-world-in-52-packs-20-polystyrene-22-12-2015

[77] Tong, T. W., & Tien, C. L. (1983). Radiative heat transfers in fibrous Insulations-Part I: Analytical study. *Journal of Heat Transfer, 105*, 70-75.

[78] Juan, L. (2011). Characteristics and fabrication technology of polyurethane aluminum foil composite air duct. *Installation, 03*, 32-34.

[79] Wheeler, L., Kitinoja, L., & Barrett, D. M. (2015). Use of insulated covers over product crates to reduce losses in amaranth during shipping delays. *Agriculture*, *5*(4), 1204-1223. doi: 10.3390/agriculture5041204

[80] *Aluminum foil heat insulation thermal break plastic pallet cover*. (2020). Retrieved September 8, 2021, from http://pengyuantech.com/product/aluminium-foil-pallet-cover-432.html

[81] Bhat, G. S., & Malkan, S. R. (2007). Polymer-laid web formation. In S. J. Russell (Ed.), *Handbook of nonwovens* (pp. 143–195). Cambridge: Woodhead Publishing Limited.

[82] Patel, M., & Bhrambhatt, D. (2011) *Nonwoven technology*. Retrieved July 10, 2020, from https://textlnfo.files.wordpress.com/2011/*10/*nonwoven-fabrics1.pdf

[83] Freeston Jr, W. D., & Platt, M. M. (1965). Mechanics of elastic performance of textile materials: Part XVI: Bending Rigidity of Nonwoven Fabrics. *Textile Research Journal*, *35*(1), 48-57.

[84] Tausif, M. (2016). *Application based approach of nonwoven industry*. Retrieved October 10, 2020, from https://www.technicaltextile.net/articles/application-based-approach-of-nonwoven-industry-7523

[85] Gupta, N. P. (1987). Influence of medullated fiber on mechanical properties and product performance. *Indian Journal of Textile Research*, *12*, 46-52.

[86] *Nonwoven fabric*. (2021). Retrieved September 8, 2021, from https://www.atextechnologies.com/medical-textile-what-we-do/medical-fabric-and-technologies/nonwoven-material/nonwoven-fabric/

[87] Sharp, A. K., & Irving, A. R. (1981). *Insulating covers for pallets of food.* Scotland: AK, Sharp.

[88] Bycroft, B. L., Brash, D. W., & Bollen, F. (1996). Using insulation and cooling to improve the asparagus cool chain. *Acta Horticulturae*, *415*, 323–332. doi: 10.17660/ActaHortic.1996.415.46

[89] Chaiwong, S., & Bishop, C. F. H. (2015). Use of an insulated bag from the supermarket to maintain 'Elsanta' strawberry temperature to households. *Acta Horticulturae, 1079*, 187–192. doi: 10.17660/ActaHortic.2015.1079

[90] Liu, Y. B. (2011). Low-temperature phosphine fumigation of chilled lettuce under insulated cover for postharvest control of western flower thrips, *Frankliniella occidentalis* (Pergande) (Thysanoptera: Thripidae). *Journal of Asia-Pacific Entomology, 14*(3), 323-325. doi: 10.1016/j.aspen.2011.02.003

[91] Sheffield. (2018). *Thermal packaging solutions: TPS insulated pallet covers*. Retrieved October 8, 2020, from https://tpsolutions.eu/pallet-covers.html

[92] *Polar Tech*. (2021). Retrieved November 10, 2021, from https://www.grainger.com/product/POLAR-TECH-Pallet-Cover-12F348

[93] *Waterproof Pallet Cover*. (2021). Retrieved November 10, 2021, from https://www.diytrade.com/china/pd/11797499/Waterproof_Pallet_Cover.html

[94] *Tyvek: A material without limits*. (2019). Retrieved September 10, 2019, from http://www.dupont.com/products-and-services/fabrics-fibers-nonwovens/protective-fabrics/brands/tyvek.html

[95] Anon. (2007). *Temperature control packaging in transit*. New Delhi: Plastics and Rubber weekly.

[96] Ashokan, P. (2011). *A comparative study for cold chain packaging options*. Retrieved September 10, 2019, from https://scholarworks.rit.edu/cgi/viewcontent.cgi?article=10233&context=theses

[97] American Society of Heating, Refrigeration, and Air Conditioning Engineers (ASHRAE). (1981). *ASHRAE handbook: Fundamentals*. Georgia: ASHRAE.

[98] Peck, R., Peter, M., Karl, K., Royce, H., . . . Andrew, G. (2015). *Passive thermal protection systems for global distribution: Qualification and operation guidance*. Retrieved September 10, 2021, from https://store.pda.org/TableOfContents/TR72_TOC.pdf

[99] Burgess, G. (1999). Practical thermal resistance and ice requirement calculations for insulating packages. *Packaging Technology and Science: An International Journal, 12*(2), 75-80.

[100] Rabl, K., Cadetti, L., & Thoreson, W. B. (2005). Kinetics of exocytosis is faster in cones than in rods. *Journal of Neuroscience, 25*(18), 4633-4640.

[101] Biddulph, P., Gori, V., Elwell, C. A., Scott, C., . . . Oreszczyn, T. (2014). Inferring the thermal resistance and effective thermal mass of a wall using frequent temperature and heat flux measurements. *Energy and Buildings, 78*, 10-16.

[102] Choi, D. S., & Ko, M. J. (2019). Analysis of convergence characteristics of average method regulated by ISO 9869-1 for evaluating in situ thermal resistance and thermal transmittance of opaque exterior walls. *Energies, 12*(10), 1989.

[103] FluxTeq. (2014). *Thermal insulation R-value measurement instruction manual*. Retrieved July 20, 2020, from http://docs.wixstatic.com/ugd/b0a63e_515aa4db3ede472fbcde9563fb0d4d63.pdf

[104] Huang, J., & Qian, X. (2008). Comparison of test methods for measuring water vapor permeability of fabrics. *Textile Research Journal, 78*(4), 342-352.

[105] Kumaran, M. K. (2006). A thermal and moisture property database for common building and insulation materials. *ASHRAE Transactions, 112*(2). 485-497.

[106] Collet, F., Chamoin, J., Pretot, S., & Lanos, C. (2013). Comparison of the hygric behaviour of three hemp concretes. *Energy and Buildings, 62*, 294-303.

CHAPTER 3

APPLICATION OF ROOM COOLING AND THERMAL INSULATION MATERIALS TO MAINTAIN QUALITY OF OKRA DURING STORAGE AND TRANSPORTATION[1]

Abstract

A combination of room cooling and the use of thermal insulation materials to maintain okra quality under simulated storage and transportation was evaluated. Okra pods were packed in plastic baskets and either cooled at 18 °C or not cooled in a room for 2 h. After either room cooling or no cooling, the okra pods were covered with three different materials: 1) perforated linear low-density polyethylene (P-LLDPE), 2) two layers of heat-reflective sheet with thin nonwoven (HRS+TNNW), and 3) metalized foam sheet (MFS). Typical handling (TP) without cooling and covering with P-LLDPE was used as the control. The six treatments were conducted during simulated storage (18 °C for 48 h) and transportation (30 °C for 15 h). Results showed that MFS gave the best insulation properties (Q_x and R-values), followed by HRS and TNNW. After room cooling, both HRS+TNNW and MFS materials delayed the time for pulp temperature to reach 18 °C (10 h), compared to P-LLDPE (2 h). TP presented the highest mass loss

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(17.8%) throughout simulated conditions, followed by cooling plus P-LLDPE (15.2%) and either of the thermal insulation materials with or without room cooling (3.6% to 5.2%), respectively. TP, cooling plus P-LLDPE, and no cooling plus MFS (44% to 56%) showed the highest percentage of decay, while cooling combined with both HRS+TNNW and MFS gave the lowest decay incidence (11–21%). Findings demonstrated that room cooling combined with HRS+TNNW had the highest efficiency for preserving cool temperature and reducing decay, compared to TP and room cooling plus MFS.

Keywords: Covering/Decay/Nonwoven/Mass loss/Metalized foam sheet

3.1 Introduction

Okra (*Abelmoschus esculentus* L.) is an economic vegetable crop widely grown in tropical and sub-tropical global regions. Okra pods are harvested when immature and eaten as vegetables [1]. Okra is an export vegetable crop of Thailand, with the Japanese market accounting for 83.3% of the total exported okra volume. The main growing areas are the central and northern areas of Thailand [2]. A decline in the quality of okra is attributable to various issues, including techniques for determining okra fruit quality, poor harvesting methods, okra harvester training levels, lack of good vehicles, terrible roads, and insufficient pre-cooling facilities [3]. High respiration rate and rapid deterioration causes heat build-up and leads to pod blackening as well as a rapid increase in okra water loss after harvesting [4-5].

Temperature and RH are the most important factors affecting the shelf life of okra [6]. The optimal storage temperature of okra ranged from 7 to 10 °C, and the pods can be stored satisfactorily for 7–10 days [7]. Fresh okra pods exhibited extremely short shelf life due to high water loss or transpiration rates. Storage of okra at 25 °C resulted in a higher mass loss (14%) compared to a lower temperature of 4 °C after 5 days due to wilting, yellowing, and decay [8]. Storage at low temperatures led to a reduction of respiration rate, transpiration, and ethylene production [9]. At high temperatures, okra

is highly susceptible to water loss, color fading, and decay, becoming squashy with a loss of commercial value and not easy to consume when fresh [10].

Heat generation, specifically known as 'Vital heat' in fresh produce, is produced as a by-product, primarily through the respiration process. Okra is classified at a very high respiration level, with a respiration rate of 40–60 mg CO_2 kg^{-1} h^{-1} and vital heat ranging from 427 to 640 J kg^{-1} h^{-1} at 5 °C [9]. Consequently, a cooling process should be taken into consideration when the storage room is designed as well as during transportation [11]. Cooling as quickly as possible after harvesting is critical to remove heat from the fresh produce and is a very important requirement for maintaining optimal product quality, especially for merchandise with naturally high respiration rates [12]. Forced-air cooling has been used for the export of okra received directly from the field [13]. In India, room cooling at 15 °C before storage at 8 °C is used for the export of okra [14]. The procedure of no cooling resulted in decreased fruit quality and increased fruit decay. Post-harvest loss of commercial fruits and vegetables increased by 25–30% when no cooling was employed through the whole storing and transporting chain, while it was only 5–10% when a cooling step at 8 °C was practiced [15]. Wang et al. [16] showed that room cooling at 2 °C reduced changes in the physiological quality of button mushroom (*Agaricus bisporus*). However, scant research has reported on cooling conditions and the efficiency of cooling processes to reduce heat generation in okra to extend storage or shelf life.

Thermal insulation materials are defined as materials or combinations of materials that retard the flow of heat to prevent or minimize temperature changes in the system or space [17]. Thermal insulation materials are normally used as pallet covering, combined with other materials, to protect fresh produce during transportation [18]. Thermal insulation material testing evaluates whether a packaging design succeeds in maintaining a temperature-sensitive product within its appropriate temperature range when exposed to ambient conditions [19]. The main thermal insulation properties are measured as thermal heat transfer and R-value. Heat transfer is the mechanism of energy movement due to temperature differences between two sources [20]. A low rate of heat transfer implies better insulation of the materials via reduction of conductive heat loss [21]. The resistance to heat flow through an insulation insulating material,

known as the R-value, is determined by ice-melt processing [22]. A higher R-value presents a better performance of thermal insulation materials [19].

Pallet cover is an alternative method used as packaging technology to reduce waste from food spoilage by minimizing temperature and humidity change during the transportation of fresh produce [18, 23-24]. Research on packaging for vegetables revealed that covering the pallet side and bottom with insulated pallet cover (Reflectix™) resulted in a reduction of mass loss and wilting in amaranth and preserved a desirable dark green col-or. Use of pallet cover for amaranth gave a high score in overall quality, with improvement on no cover [18]. Liu [25] reported the use of an insulated cover to keep pre-chilled lettuce at low temperatures. The insulated cover was also suitable for low-temperature phosphine fumigation to control western flower thrips on harvested lettuce. Chaiwong and Bishop [23] reported on lightweight insulation bags. Results showed that insulated bags provided cool temperature management and reduced the cool chain breakdown of strawberries from the supermarket to domestic refrigerators. The insulated pallet covers also gave better temperature preservation compared to no cover, and temperature changes occurred more slowly in chard, cucumber, and carrot [18, 23-24]. However, very few studies exist about the use of thermal insulation cover to prevent post-harvest losses of okra under different temperature conditions.

The main post-harvest problems of okra during domestic transportation are temperature and RH fluctuation. These lead to physiological damages such as wilting and fruit rot before the freeze-drying process. Cooling treatment could delay the deterioration of okra quality, whereas thermal insulation covering could improve control-ling temperature and humidity fluctuations under typical truck transportation. In this study, the efficiency of room cooling and thermal insulation materials in controlling cool temperature and okra quality under simulated storage and transportation were evaluated.

3.2 Material and Methods

3.2.1 Materials Properties

Thermal heat energy was determined according to the procedure of Harvey [21], using an expanded polystyrene box with dimensions (75 × 38 × 38.5 cm^3) with two sections (Figure 3.1). The material sample was taped on a hole (C) 10 cm × 10 cm to allow heat from the heated copper coil (E) at temperature 45 °C in section 1 (A) to pass through the material sample and enter section 2 (B). Temperature data loggers (Tinytag Talk 2: TK-4014-PK, Gemini Data Loggers, West Sussex, UK) were used to monitor the temperature change between the two sections (section 1 (I) and section 2 (J)) of the box for 3 h until a constant temperature was recorded. The rate of transfer of thermal heat energy (Q_x) in J s^{-1} was calculated.

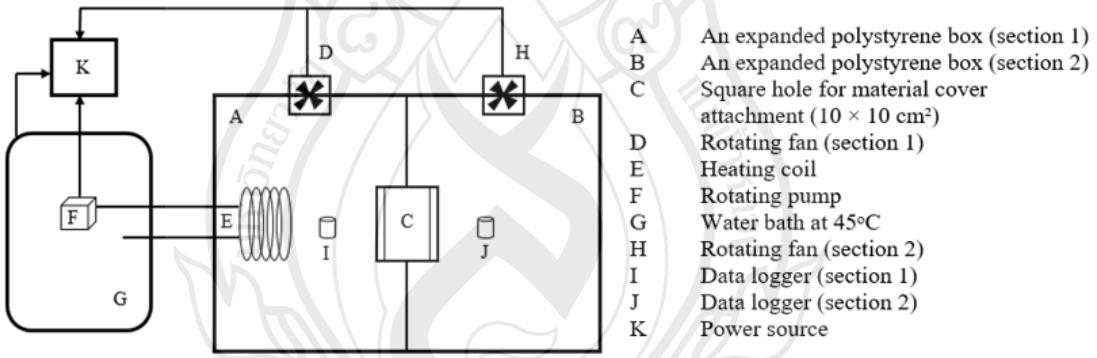


Figure 3.1 Schematic Diagram for Heat Transfer Test Through Material Covers at the Laboratory

The water vapor permeability (WVP) through different materials was determined using the desiccant in cup method. Following ASTM E96 [26], the specimen or cover material was sealed on the open mouth of a test dish containing a desiccant, and the test dish was placed in a constant climate chamber (KBF-115, Binder, Tuttlingen, Germany) at 25 °C and 50% RH. Water vapor permeability was then calculated as rate of water vapor transmission in g $h^{-1}m^{-2}$.

Air permeability was determined using an air permeability tester (FX 3300 LabAir IV, Textest Instruments, Schwerzenbach, Switzerland) according to ASTM D737-04 [27]. Thermal insulation materials were cut into square pieces of 20 × 20 cm and measured for air permeability (l m^{-2} s^{-1}). The R-value was determined as resistance to heat flow through the thermal insulation material using the ice-melt test, following Singh et al. [19]. In this method, 2000 g of ice were placed in a non-metallic bucket, which was then positioned in the center of a basket inside thermal insulation bags and wrapped tightly with tape. The package was stored on a shelf at ambient temperature (25 °C) for 12 h. At the end of the test, the thermally insulated containers were opened, and water was collected from the buckets. The weight of water was recorded to calculate the melt rate (m^2 °C W^{-1}). Five samples (replications) in each material were tested.

3.2.2 Plant Material

'Lady Finger' okra pods from Green Global Seeds Company Limited, Thailand, were planted with the spacing between plant and row of 50 and 100 cm, respectively, with sprinkler irrigation. The okra pods were harvested 45 days after planting, or 6 days after flowering from an okra plantation (20°13′27.2″ N 99°50′05.2″ E), in Mae Chan district, Chiang Rai Province. The pods were transported from the farm to the Postharvest Laboratory at Mae Fah Luang University within 30 min. After arrival at the laboratory, the okra pods were graded to uniform size of pod length 7–11 cm (the specific size for okra processing), with minimum requirements being green in color, free of distinct signs of bruising, disease, and a clean-cut pedicel.

3.2.3 Experimental Treatments and Heat from Respiration Rate (RR)

The research study was divided into two experiments.

1. Handling procedures

Six treatments were studied. The control, as typical handling (TP) of the Phayao community enterprise (without room cooling and covered with perforated linear low-density polyethylene (P-LLDPE)) was compared with developing handling (DH), comprising room cooling, covered by two thermal insulation materials (heat-reflective sheet (HRS) + thin nonwoven (TNNW)), which were polypropylene (PP)-based spunbond nonwoven, and metalized foam sheet (MFS)), as shown in Table 3.1. It is

noted that the HRS material was evenly perforated and distributed with a pin of diameter 0.55 mm for a total perforation area of 0.09 cm^2.

Table 3.1 Six Treatments (with or without room cooling) using Different Material Covers

Treatment	Description
TP (Control)	No room cooling with P-LLDPE covering
DH1	Room cooling with P-LLDPE covering
DH2	No room cooling with HRS + TNNW covering
DH3	No room cooling with MFS covering
DH4	Room cooling with HRS + TNNW covering
DH5	Room cooling with MFS covering

For each treatment, 1500 g of okra pods were packed in a plastic basket (five replications). Initial temperature at the core of the okra pods was approximately 30 °C. Room cooling treatments (DH1, DH4 and DH5) were performed by setting the cooling medium at 0 °C for 2 h, compared with a cool room at 18 °C (no room cooling) (TP, DH2, and DH3) for 2 h as the 7/8 cooling time. Pulp temperature of the okra was monitored by a multi-channel data logger (Hioki, LR8431, Nagano, Japan) connected with a type-K thermocouple for 10 channels. Five baskets each room cooling at 0 °C or at 18 °C were allocated for temperature monitor. After room cooling, the okra pods were covered with different thermal insulation materials, except for TP and DH1. Storage and transportation conditions of okra to simulate commercial practice before processing comprised storage at 18 °C for 48 h and transfer at 30 °C for 15 h.

2. Determination of respiration rate

Respiration rate of okra was determined under three storage conditions (10, 20, 30 °C) for 2 and 3 days. Okra pods (150 g) were packed in a plastic food container (8400 mL) (Figure 3.2). Respiration rate testing was conducted in a closed system for 2 h. A gas sample of 5000 µL was drawn from each container at daily intervals for gas

chromatography (GC) analysis. A gas chromatograph (7890A, Agilent Technologies, California, USA) equipped with a thermal conductivity detector (TCD) and HayeSep Q column (80/100 mesh, 3.05-m long) was used to analyze the gas samples. Nitrogen was used as the carrier gas at a flow rate of 52.2 mL min^{-1} with split mode. Injector, oven, and detector temperature conditions were 150, 60, and 275 °C, respectively. The respiration rate (R_{CO2}) was determined on days 2 and 3 for the three storage conditions and calculated by the following formula.

$$R_{CO2}\ (\text{mg } CO_2\ kg^{-1}\ h^{-1}) = \frac{(((CO_2\ (\%) \times \text{volume of container (ml)})/100)/\ \text{fruit weight (kg)})}{\text{(closing time)}}$$

The respiration rate (R_{CO2}) of okra pods in each closed system storage condition was calculated as the temperature coefficient (Q_{10}) value by formula:

$$Q_{10} = (R_2/R_1)^{10/(T_2 - T_1)}$$

where R_2 and R_1 are the respiration rate at temperature T_2 and T_1, respectively [28].

Figure 3.2 Okra Pods Packed in a Plastic Food Container for Respiration Rate Measurement by a Closed System

The Q_{10} values on day 2 (48 h) and day 3 (72 h) were used to estimate the respiration rate of okra pods (R_C) in different air temperature levels using a temperature data logger (Tinytag Talk 2: TK-4014-PK, Gemini Data Loggers, West Sussex, UK).

This depended on the thermal insulation cover treatments under simulated storage (18 °C for 48 h) and transportation (30 °C for 15 h), respectively. The air temperature for estimation of okra respiration rate (R_C) in each cover treatment was determined from the final air temperature level before simulated storage (R_{C1}) and transportation conditions (R_{C2}). Respiration rates of okra pods in each cover material were converted into vital heat by formula [29]:

$$\text{Vital heat (J kg}^{-1}\text{ h}^{-1}\text{)} = R_C \times 10.7$$

where R_C = respiration rate of okra pods in each cover treatment.

3.2.4 Temperature and RH Monitoring

Air temperatures inside the covering and pulp temperatures at the core of the okra pods were measured using a temperature data logger for air temperature (Tinytag Talk 2: TK-4014-PK, Gemini Data Loggers, West Sussex, UK) with three replications and pulp temperature (Tinytag Talk 2: TK-4023-PK, Gemini Data Loggers, West Sussex, UK) with four replications. RH inside the covering was recorded using a temperature and RH data logger (Tinytag Ultra 2: TGU-4500, Gemini Data Loggers, West Sussex, UK) at 30 s intervals. Pulp temperature was analyzed using temperature profile and boxplot at 12 h after simulated storage with stable temperature level. After simulated transportation at 30 °C for 15 h, air and pulp temperature levels were analyzed using a boxplot at 1 h 30 min (air temperature of TP at 25 °C) and 15 h after simulation, and the rate of change during temperature rise after simulated transportation was calculated. Data analysis of both air and pulp temperature focused on the data point at 25 °C and temperature range from 25 °C to 30 °C. Furthermore, heatmap analysis represented pulp temperature levels after simulated storage and transportation for 12 h. Python 3.6.9 was used to create the heatmap chart. The packages Seaborn version 0.11.1, Pandas version 1.1.5, and Matplotlib version 3.2.2 were all required by heatmap. The profile of RH throughout the experiment was also investigated.

3.2.5 Mass Loss Determination

Mass loss of the okra pods was determined using an electric weighing balance (Pioneer^{TM}, Ohaus, NJ, USA). Percentage mass loss (%) was calculated on the basis of initial weight (IW) before cooling and final weight (FW) at the end of simulated storage and transportation, using WL (%) = [(IW – FW)/IW] × 100 [30].

3.2.6 Determination of Decay Incidence

The first sign of okra deterioration was observed as a small wet lesion on pod, and then the entire pod coated with a grayish-white mass of mold. The okra pods were evaluated when incidence of decay occurred, calculated based on weight of pods showing symptoms of decay (D), and classified into four categories, including <10% of decay occurrence, 10–25% of decay occurrence, 25–50% of decay occurrence, and >50% of decay occurrence. Percentage decay (%) was calculated on the basis of total weight of pods per plastic basket (TW), using D (%) = [(D/TW) ×100] [30]. Incidence of decay was determined at the end of simulated storage and transportation.

3.2.7 Statistical Analysis

SPSS for Windows version 20 (SPSS Inc., Chicago, IL, USA) was used for the statistical analysis. Data analysis for the estimated respiration rate with three replicates, averaged pulp temperature in heatmap chart with four replicates as well as material properties, mass loss, and incidence of decay with five replicates compared by mean at a significant level of 0.05 using Tukey's HSD post hoc test.

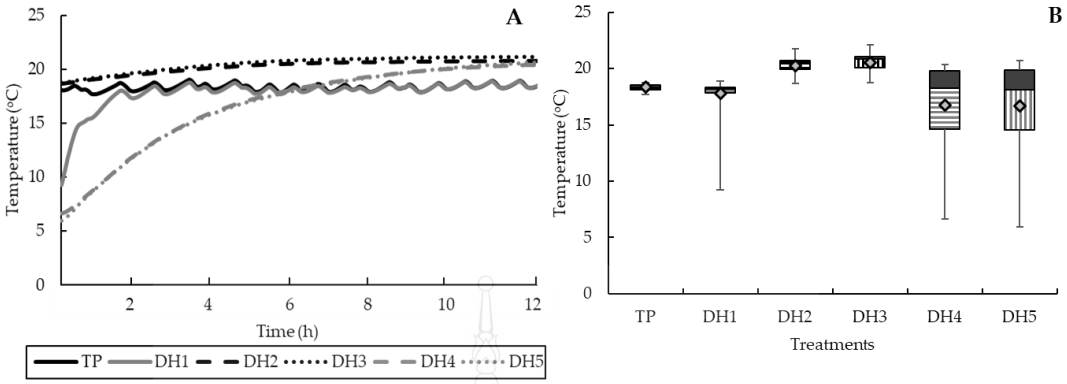
3.3 Results and Discussion

3.3.1 Materials Properties

The properties of the thermal insulation materials, including thickness, thermal heat energy, WVP, air permeability, and R-value, are shown in Table 3.2. Temperature transfer through the material was studied in terms of the heat transfer processes. Heat transfer is the process of energy movement caused by temperature differences [20]. Lower thermal heat energy (Q_x) value shows a lower heat transfer rate (good insulator) through the sub-stance layer, while higher Q_x shows a higher heat transfer rate (poor

insulator) through the layer [21]. In this study, results indicated that MFS with a thickness of 3.1 mm gave the lowest heat transfer property (Q_x =1.53 J s^{-1}), compared to the other three materials, while P-LLDPE (0.120 mm) had the highest Q_x value (3.85 J s^{-1}). A combination of HRS (1.450 mm) (2.57 J s^{-1}) and TNNW (0.270 mm) (3.23 J s^{-1}) showed improved insulation property and potential for prototype development for covering material in the future. The high insulation properties of MFS and HRS materials may be partly due to greater thickness. Material with lower thermal heat energy (Q_x) also tends to have a higher R-value. MFS had the highest R-value (0.225 m^2 °C W^{-1}), followed by HRS (0.211 m^2 °C W^{-1}), TNNW (0.187 m^2 °C W^{-1}), and P-LLDPE (0.153 m^2 °C W^{-1}), respectively (Table 3.2). Results showed that MFS and HRS preserved cool temperatures better than the other materials (Figure 3.3).

For water vapor permeability (WVP), a partial pressure difference between the inside and outside of the test material affects the gain or loss of moisture in the product [31]. In this study, TNNW and P-LLDPE showed higher WVP than MFS and HRS and would be suitable for highly breathable fruits (Table 3.2). High WVP material had the potential to eliminate vapor condensation, thus inhibiting microbial activity [31]. On the other hand, both MFS and HRS materials had lower WVP values and air permeability, which may cause vapor condensation inside the covering (Table 3.2). Interestingly, a combination of HRS and TNNW showed good performance in terms of insulation and water and air permeability properties, with the potential to maintain cool temperatures and protect condensation inside the package or cover.



Note Boxes indicate the lower and upper quartile. The horizontal line in each box represents the median temperature. Mean temperature for each treatment is indicated by ♦. Vertical lines extending above and below each box represent minimum and maximum temperature recorded. Six treatments were no room cooling with P-LLDPE covering (TP as control), room cooling with P-LLDPE covering (DH1), no room cooling with HRS + TNNW covering (DH2), no room cooling with MFS covering (DH3), room cooling with HRS + TNNW covering (DH4), room cooling with MFS covering (DH5)

Figure 3.3 Pulp Temperature Profiles during Simulated Storage at 18 °C for 12 h (A) and Boxplot of Pulp Temperature Profiles during Simulated Storage at 18 °C for 12 h (B)

Table 3.2 Covering Material Properties (thickness, thermal heat energy, WVP, R-value and air permeability)

Material	Thickness (mm)	Thermal Heat Energy ($Q_x \times 10^{-4}$) (J s^{-1})	R-Value (m^2°C W^{-1})	Water Vapor Permeability (g $h^{-1}m^{-2}$)	Air Permeability (l m^{-2} s^{-1})
P-LLDPE	0.120 ± 0.03 [d]	3.85 ± 0.06 [a]	0.153 ± 0.01 [d]	0.325 ± 0.04 [a]	172.80 ± 12.05 [b]
TNNW	0.270 ± 0.20 [c]	3.23 ± 0.07 [b]	0.187 ± 0.01 [c]	0.450 ± 0.05 [a]	945.60 ± 43.21 [a]
HRS	1.450 ± 0.43 [b]	2.57 ± 0.12 [c]	0.211 ± 0.02 [b]	0.000003 ± 0.00 [b]	0.59 ± 0.01 [d]
MFS	3.100 ± 0.08 [a]	1.53 ± 0.06 [d]	0.225 ± 0.01 [a]	0.000012 ± 0.00 [b]	49.42 ± 0.21 [c]

Note Different letters for different mean levels in each parameter for Tukey's HSD post hoc test indicate significant differences at $p < 0.05$. Values are mean ±S.E. from five replicates. Four materials were perforated linear low-density poly-ethylene (P-LLDPE), heat-reflective sheet (HRS), thin nonwoven (TNNW), and metalized foam sheet (MFS)

3.3.2 Respiration Rate, Q_{10} Value, and Heat from Respiration Rate

An increase in storage temperature and time resulted in a rise in okra respiration rate. Respiration rate at three storage conditions (10, 20, 30 °C) for 2 days increased gradually from 186.39 (10 °C) to 355.44 (30 °C) mg CO_2 kg^{-1} h^{-1} as well as on day 3 (Table 3.3). Similarly, Hardenburg et al. [7] reported that higher storage temperature at 25–27 °C (328–362 mg CO_2 kg^{-1} h^{-1}) increased respiration rate compared to lower temperatures at 5 °C (59 mg CO_2 kg^{-1} h^{-1}) and 10 °C (86 to 95 mg CO_2 kg^{-1} h^{-1}). Furthermore, the widely used Q_{10} value represents an improvement in the rate of a process with a 10 °C increase in temperature [32]. In this study, the Q_{10} value of temperature range (10–20 °C) on days 2 and 3 increased from 1.17 to 1.87, while the Q_{10} value of temperature range (20–30 °C) decreased from 1.50 to 1.37 (Table 3). In lower temperature storage, Q_{10} value is typically less than 2.00 levels, whereas Q_{10} value gradually decreased in higher temperature conditions [33]. However, Q_{10} values of okra during different storage temperatures have never been reported. Yasunaga et al. [34] reported that Q_{10} value of cucumber at 10 to 20 °C was 4.37 and dramatically decreased to 1.89 with higher temperature storage at 20–30 °C. In this study, to estimate okra respiration rate under simulated storage (R_{C1}) and transportation (R_{C2}), the Q_{10} value was calculated for respiration rate in each cover treatment and converted to vital heat as shown in Tables 3.4 and 3.5, respectively.

Table 3.3 Rate of Respiration of Okra Pods at Different Storage Conditions (10, 20, and 30 °C) for 2 and 3 Days in a Closed System

Temperature (°C)	R_{CO2} (mg CO_2 kg^{-1} h^{-1})		Q_{10}	
	Day 2	Day 3	Day 2	Day 3
10	186.39	207.33		
			1.17	1.87
20	237.70	325.63		
			1.50	1.37
30	355.44	444.61		

The efficiency of room cooling and thermal insulation materials under simulated storage and transportation conditions for respiration rate and heat from respiration (vital heat) was studied. Table 3.4 shows that respiration rates and vital heat levels in DH4 and DH5 were lower than in the other three treatments under simulated storage at 18 °C for 48 h. After room cooling at 0 °C for 2 h, the field heat and vital heat of okra were removed and reduced to around 20% of no room cooling before the cool storage condition. However, no difference was shown between no room cooling plus either P-LLDPE or insulated materials (HRS + TNNW, MFS), as well as room cooling with P-LLDPE. A decrease in vital heat in okra suggested that room cooling combined with insulated material cover should be employed. During simulated transportation at 30 °C for 1 h, the vital heat of DH2, DH3, and DH5 (5148–5202 J kg^{-1} h^{-1}) was lowest compared with TP and DH1, and DH4 treatments (5791–5873 J kg^{-1} h^{-1}). However, at a longer period of simulated transportation for 15 h, vital heat levels in all DH treatments were similar to TP. The efficiency of thermal insulation materials reduced the vital heat loss for a short period of around an hour. Either room cooling or no room cooling with thermal insulation material covering reduced heat from respiration under heat stress conditions over a short period (Table 3.5).

Table 3.4 Estimated Respiration Rate (R_{C1}) and Vital Heat Among the Six Treatments under Simulated Scheme 18 °C for 48 h

Treatment	Rc_1 (mg CO_2 kg^{-1} h^{-1})	Vital heat (J kg^{-1} h^{-1})
TP	329 ± 0.0 [a]	3522 ± 0.1 [a]
DH1	329 ± 0.0 [a]	3522 ± 0.1 [a]
DH2	330 ± 0.8 [a]	3529 ± 8.1 [a]
DH3	330 ± 0.9 [a]	3536 ± 9.3 [a]
DH4	214 ± 0.4 [b]	2288 ± 4.7 [b]
DH5	218 ± 1.9 [b]	2329 ± 20.1 [b]

Note Different letters for different mean levels in each parameter for Tukey's HSD post hoc test indicate significant differences at $p < 0.05$. Values are mean ±S.E. from three replicates. Six treatments were no room cooling with P-LLDPE covering (TP as control), room cooling with P-LLDPE covering (DH1), no room cooling with HRS + TNNW covering (DH2), no room cooling with MFS covering (DH3), room cooling with HRS + TNNW covering (DH4), room cooling with MFS covering (DH5)

Table 3.5 Estimated Respiration Rate (R_{C2}) and Vital Heat Among the Six Treatments under Simulated Transportation at 30 °C for 1 h (air temperature of TP at 25 °C) and 15 h (the end of simulated transportation)

Treatment	Rc_2 (mg CO_2 kg^{-1} h^{-1}) at 1 h	Vital Heat (J kg^{-1} h^{-1}) at 1 h	Rc_2 (mg CO_2 kg^{-1} h^{-1}) at 15 h	Vital Heat (J kg^{-1} h^{-1}) at 15 h
TP	541 ± 4.7 [a]	5791 ± 49.0 [a]	640 ± 0.3	6853 ± 3.1
DH1	549 ± 2.6 [a]	5873 ± 28.5 [a]	646 ± 0.6	6914 ± 6.3
DH2	486 ± 6.1 [b]	5202 ± 66.3 [bc]	633 ± 4.0	6774 ± 42.5
DH3	483 ± 4.7 [b]	5167 ± 49.7 [bc]	629 ± 8.2	6732 ± 87.4
DH4	506 ± 2.7 [b]	5413 ± 28.0 [b]	632 ± 3.2	6768 ± 34.3
DH5	481 ± 8.4 [b]	5148 ± 88.4 [c]	645 ± 3.8	6900 ± 40.9

Note Different letters for different mean levels in each parameter for Tukey's HSD post hoc test indicate significant differences at $p < 0.05$. Values are mean ±S.E. from three replicates. Six treatments were no room cooling with P-LLDPE covering (TP as control), room cooling with P-LLDPE covering (DH1), no room cooling with HRS + TNNW covering (DH2), no room cooling with MFS covering (DH3), room cooling with HRS + TNNW covering (DH4), room cooling with MFS covering (DH5)

3.3.3 Air and Pulp Temperature Levels of Okra

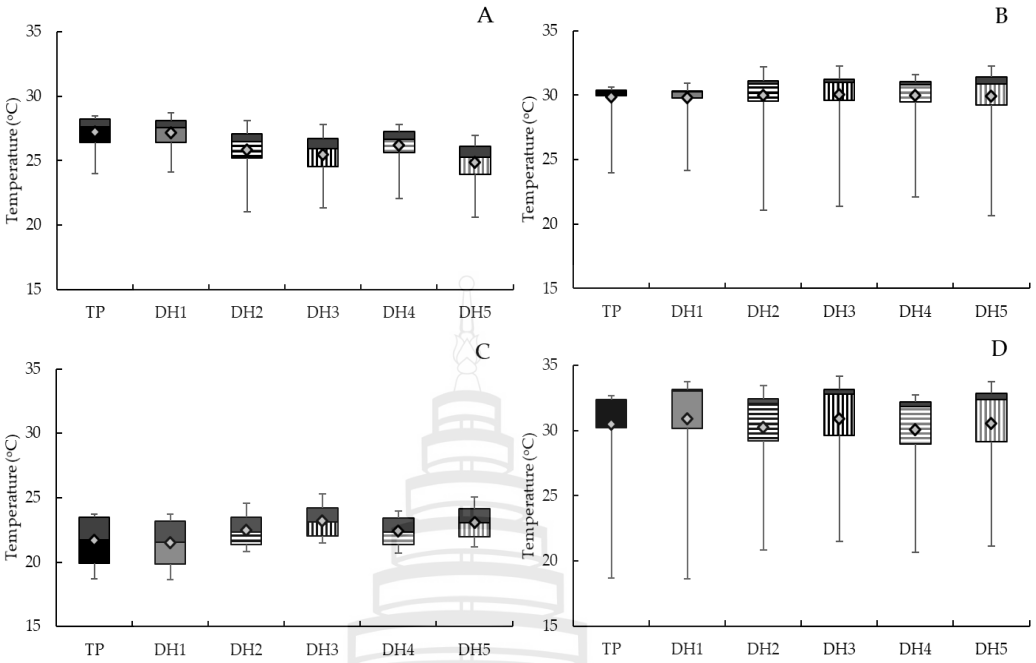
Room cooling and thermal insulation materials showed efficient cooling under simulated storage and transportation. After simulated storage at 18 °C for 12 h, okra pulp temperature profiles of room cooling treatments (DH1, DH4, and DH5) maintained cool temperature for around 10 h, better than no room cooling treatments (TP, DH2, and DH3). The use of two thermal insulation materials (HRS and MFS) combined with room cooling (DH4 and DH5) maintained cool temperatures, compared to no cover. In addition, the combination of room cooling and thermal insulation as a covering material effectively maintained cool temperature (Figure 3.3A). Temperature control of cover treatments was presented as a boxplot (Figure 3.3B) which showed the

mean (rhombuses), lowest (lower error bars), and highest temperature (upper error bars) levels. Okra pulp temperature in DH4 and DH5 had the lowest mean temperature (17 °C) compared to the other four treatments (19 °C for TP and DH1; 20 °C for DH2 and DH3). The use of thermal insulation materials without room cooling (DH2 and DH3) gave the significantly highest pulp temperature (highest upper error bars) as well as the warmest level (highest lower error bars) after simulated storage at 18 °C for 48 h. This was presented as a narrow range of cool temperature levels (a smaller boxplot) compared with room cooling (DH4 and DH5) (a larger boxplot).

To simulate actual transportation for 15 h, we designed an experiment to analyze when the air temperature of TP reached a constant level at 25 °C. Thermal insulation materials maintained a cool temperature (average and minimum temperature levels) better, compared to either no covering or covering with P-LLDPE (TP and DH1). However, thermal insulation materials tended to build up pulp temperature (Figure 3.4C, D). The minimum air and pulp temperatures inside thermal insulation materials were the lowest. (Figure 3.4A, B). As no published reports were available concerning the effect of room cooling combined with thermal insulation covering under storage and transportation conditions on the quality of okra, the results of this study were compared to published data for other fresh fruits and vegetables. Bollen et al. [35] used low-temperature cooling in combination with pallet covers for asparagus. They found that the use of covering with insulation materials reduced heat generated by fresh produce with high respiratory rates inside the covering. Long-term covering was recognized as a problem due to heat accumulation, leading to a higher temperature than no cover. Other studies reported that thermal insulation covers showed better temperature preservation than no cover, and temperature changes occurred more slowly than with no cover in amaranth [18], strawberries [23], and chard, cucumber, and carrot [24]. However, in this study, both temperature profiles increased to 30 °C within 15 h (Figure 3.4B, D). Covering with thermal insulation materials maintained cool temperature (<25 °C) under a high-temperature environment for less than 6 h. Additionally, the pulp temperature levels after simulated storage and transportation are presented in the heatmap chart (Figure 3.5) as a matrix of red–blue color tones with average temperature in each hour for 12 h. At the simulated storage (Figure 3.5A), DH4 and DH5 had a significantly low average of pulp temperature (blue color tone), while

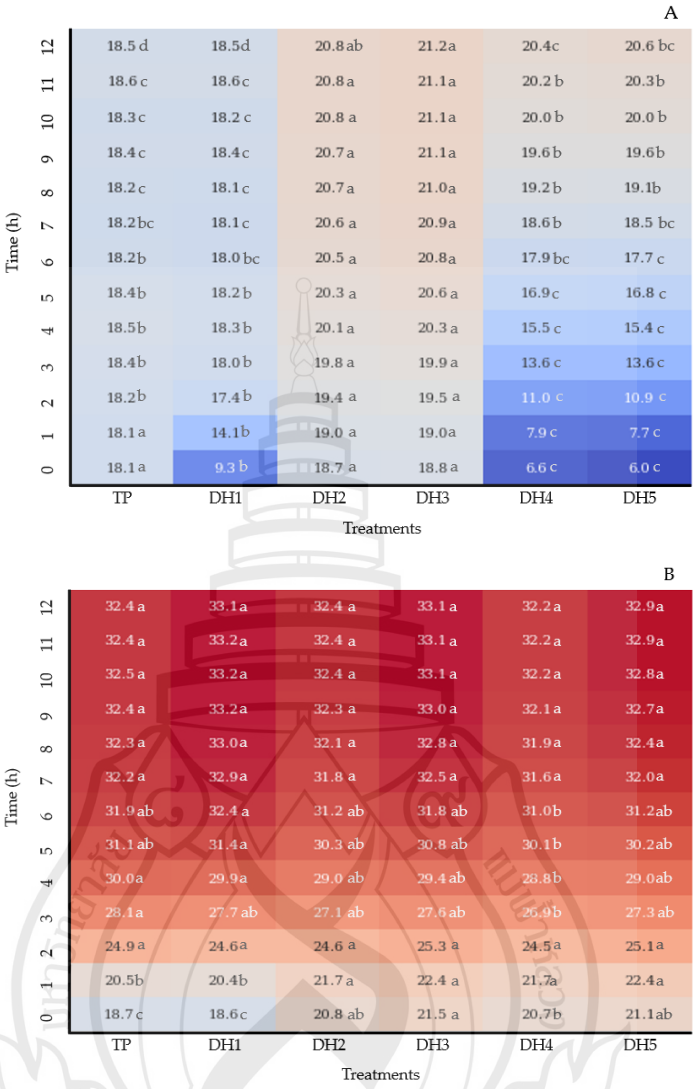
DH2 and DH3 had a significantly high average of pulp temperature (light orange color tone) that related to the highest pulp temperature profiles (Figure 3.3A) and the smallest box-plot size with the lowest pulp temperature profiles when compared among the five treatments (Figure 3.3B). Moreover, the heatmap chart during simulated transportation (Figure 3.5B) showed that the use of thermal insulation materials (DH2, DH3, DH4, and DH5) caused a heat accumulation (light orange color tone) within an hour, then there was no significant difference among all treatments after an hour. The combination of room cooling and thermal insulation materials (DH4 and DH5) increased the efficiency of maintaining cool temperature more than using thermal insulation materials without room cooling (DH2 and DH3).

Table 3.6 compares the air temperature change rate inside the covering under simulated transportation testing. TP and DH1 showed the lowest rates of temperature change, whereas no cover in TP and DH1 treatments showed reduced control of cool temperature due to either high air ventilation through the plastic basket or no thermal insulation covering, respectively, indicating the highest thermal heat energy (Q_x) and lowest R-value of P-LLPPE (Table 3.2). P-LLDPE gave poor preservation of cool temperature during simulation compared with the other materials. By contrast, low pulp temperature change rate showed high effectiveness of thermal insulation materials (TNNW, HRS, and MFS) for DH2 to DH5 by maintaining cool pulp temperature (Table 3.6). In previous studies, cardboard in combination with plastic foil of bottle beer gave control cold temperature than hard plastic crate under air temperature condition at 30 °C due to a reduction of the air movement and transferring contribution of the beer bottle as well as a reduction of vibration damping during transportation [36]. The efficiency of a base material nonwoven fabric on temperature-controlled deliveries was studied by Dieckmann et al. [37]. Nonwoven feather fiber composite isolation gave greater material performance aspects than EPS in terms of thermal insulation, and inexpensive, sustainable, and lightweight material. In this study, HRS and MFS-based aluminum foil material and nonwoven performed good thermal insulation. However, the browning incidence of okra pods also caused vibration damage during handling and transportation. Interestingly, further research should be conducted to investigate the combined effects of thermal insulation materials on cold temperature control and vibration damage reduction during transportation.



Note An interpretation of the box plot graph is presented as a caption in Figure 3. Six treatments were no room cooling with P-LLDPE covering (TP as control), room cooling with P-LLDPE covering (DH1), no room cooling with HRS + TNNW covering (DH2), no room cooling with MFS covering (DH3), room cooling with HRS + TNNW covering (DH4), room cooling with MFS covering (DH5)

Figure 3.4 Air Temperature Profile after 1 h 30 min (A) and 15 h (B), Pulp Temperature Profile after 1 h 30 min (C) and 15 h (D) during Simulated Transportation at 30 °C



Note Different letters in each row indicate significant differences of mean temperature from four replicates for pulp temperature in each hour at $p < 0.05$. Six treatments were no room cooling with P-LLDPE covering (TP as control), room cooling with P-LLDPE covering (DH1), no room cooling with HRS + TNNW covering (DH2), no room cooling with MFS covering (DH3), room cooling with HRS + TNNW covering (DH4), room cooling with MFS covering (DH5)

Figure 3.5 Heatmap Chart of Pulp Temperature Profiles during Simulated Storage at 18 °C for 12 h (A) and Simulated Transportation at 30 °C for 12 h (B)

Table 3.6 Rate of Changes in Air and Pulp Temperature under Simulated Transportation at 30 °C for 15 h

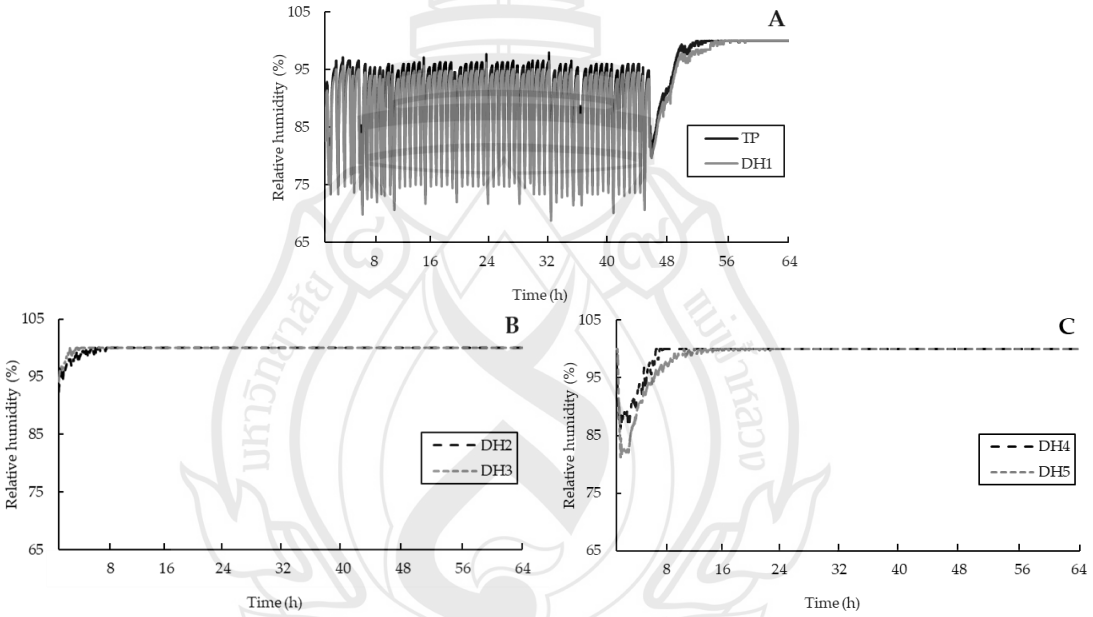
Treatment	Rate of Temperature Changes (°C h^{-1})			
	Air Temperature		Pulp Temperature	
	T_1–25 °C	25 °C–30 °C	T_1–25 °C	25 °C–30 °C
TP	7.54 ± 0.17 ^{b}	1.40 ± 0.02 ^{a}	4.26 ± 0.20 ^{a}	2.64 ± 0.15 ^{a}
DH1	7.34 ± 0.21 ^{b}	1.40 ± 0.01 ^{a}	4.00 ± 0.11 ^{a}	2.58 ± 0.02 ^{ab}
DH2	9.56 ± 0.47 ^{ab}	1.13 ± 0.04 ^{b}	2.55 ± 0.08 ^{b}	2.02 ± 0.05 ^{bc}
DH3	10.30 ± 1.41 ^{ab}	1.32 ± 0.05 ^{a}	2.50 ± 0.08 ^{b}	1.88 ± 0.15 ^{c}
DH4	11.69 ± 0.47 ^{a}	1.14 ± 0.03 ^{b}	2.59 ± 0.10 ^{b}	1.83 ± 0.08 ^{c}
DH5	9.25 ± 0.45 ^{ab}	1.08 ± 0.04 ^{b}	2.75 ± 0.18 ^{b}	1.75 ± 0.15 ^{c}

Note. T_1 is the temperature at the end of the simulated storage. Different letters in different mean levels of each parameter for Tukey's HSD post hoc test indicate significant differences at $p < 0.05$. Values are mean ±S.E. from five replicates. Six treatments were no room cooling with P-LLDPE covering (TP as control), room cooling with P-LLDPE covering (DH1), no room cooling with HRS + TNNW covering (DH2), no room cooling with MFS covering (DH3), room cooling with HRS + TNNW covering (DH4), room cooling with MFS covering (DH5)

3.3.4 RH Inside Covering Materials

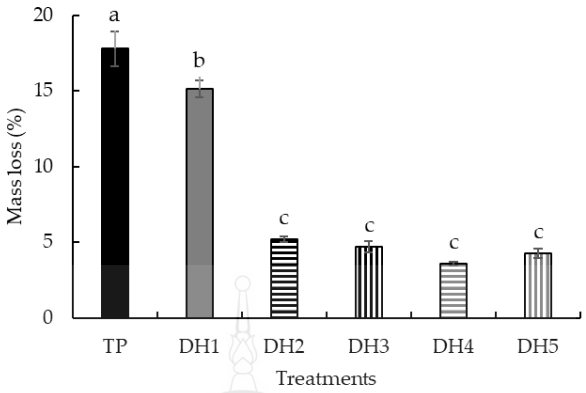
RH was monitored during simulated storage and transportation. RH of TP and DH1 as no covering (75%) (Figure 3.6A) was lower than all the other thermal insulation materials (100% RH) (Figure 3.6B, C) after storage for 48 h. This showed that the use of thermal insulation materials for covering preserved RH fluctuation inside the covering was better than without covering (Figure 3.6B, C). Low RH in TP and DH1 increased mass loss (>15%), while thermal insulation covers with 100%RH reduced mass loss (5%) throughout this simulation (Figure 3.7). The effect of RH on the quality of 'Niitaka' pears was studied by Lim et al. [38] using two types of pallet covers made of polyethylene film to maintain high RH in commercial low-temperature storage

rooms. Use of pallet covers increased RH from 83 to 87% or 93 to 95% for open and closed pallet covers, respectively. Moreover, using insulated material for covering preserved the RH inside the covering and was better than no covering during shipping delays in amaranth [18]. Covering with thermal insulation materials maintained the highest RH level (100% RH) after 12 h, particularly HRS and MFS (Figure 3.6). This result related to the lowest WVP level of HRS and MFS materials, which preserved the RH inside the covering (Table 3.2). On the other hand, low WVP of MFS caused condensation inside the covering and accelerated the activity of microorganisms with an increase of decay incidence (Figure 3.8).



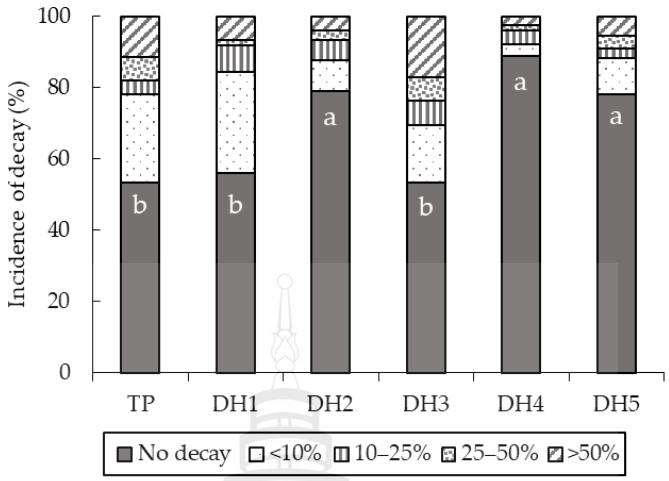
Note Six treatments were no room cooling with P-LLDPE covering (TP as control), room cooling with P-LLDPE covering (DH1), no room cooling with HRS + TNNW covering (DH2), no room cooling with MFS covering (DH3), room cooling with HRS + TNNW covering (DH4), room cooling with MFS covering (DH5)

Figure 3.6 RH Profiles Among Treatments, including TP and DH1 (A), DH2 and DH3 (B), DH4 and DH5 (C), after Simulated Storage at 18 °C for 48 h and Simulated Transportation at 30 °C for 15 h



Note Different letters in different mean levels of each parameter for Tukey's HSD post hoc test indicate significant differences at $p < 0.05$. Values are mean ± S.E. from five replicates. Six treatments were no room cooling with P-LLDPE covering (TP as control), room cooling with P-LLDPE covering (DH1), no room cooling with HRS + TNNW covering (DH2), no room cooling with MFS covering (DH3), room cooling with HRS + TNNW covering (DH4), room cooling with MFS covering (DH5)

Figure 3.7 Mass Loss (%) among the Six Treatments after Simulated Storage at 18 °C for 48 h and Simulated Transportation at 30 °C for 15 h



Note Different letters in different mean levels of each parameter for Tukey's HSD post hoc test indicate significant differences at $p < 0.05$. Values are mean ±S.E. from five replicates. Six treatments were no room cooling with P-LLDPE covering (TP as control), room cooling with P-LLDPE covering (DH1), no room cooling with HRS + TNNW covering (DH2), no room cooling with MFS covering (DH3), room cooling with HRS + TNNW covering (DH4), room cooling with MFS covering (DH5)

Figure 3.8 Incidence of Decay (%) among the Six Okra Treatments after Simulated Storage at 18 °C for 48 h and Simulated Transportation at 30 °C for 15 h

3.3.5 Mass Loss of Okra

Okra pods in TP and DH1 (no cover and P-LLDPE covering) lost a significant amount of fresh weight (around 15%) compared to thermal insulation material treatments (5%) (Figure 3.7). This corresponded to better performance in maintaining lower temperature and higher RH by thermal insulation materials (Figures 3.3 and 3.6). There was no significant difference between room cooling or no cooling combined with thermal insulation materials (Figure 3.7). However, limited data exist com-paring the efficiency of thermal insulation covering on mass loss of fresh produce. Wheeler et al. [18] reported that amaranth contained in uncovered pallets had more weight (11.0%) than in pellets covered with Reflectix^{TM} insulation material (2.0%) (bubble pack insulation consisted of reflective aluminum foil and heavy gauge polyethylene) over a

6 h storage cycle. Reflectix^{TM} cover effectively minimized the amount of moisture loss during amaranth storage. Macnish et al. [39] compared the performance of four propriety pallet cover systems (CO_2 West, PEAKfresh, PrimePro, and Tectrol) in maintaining the quality of strawberry fruit during transportation with a temperature at 20 °C. Results showed that pallet cover systems significantly reduced transport-related mass loss by less than 0.5%, compared to those with control or no cover material (0.8%). Similarly, Lim et al. [38] found that the use of pallet cover in pear storage for 7 days reduced mass loss compared to no pallet cover. The application of pallet cover is an alternative technique for controlling temperature and humidity fluctuation during transportation [40] as well as reducing the rate of mass loss [41]. In this study, low mass loss of okra in thermal insulation covers after simulation (Figure 3.7) was related to low levels of WVP (Table 3.2).

3.3.6 Incidence of Decay (ID)

Highly significant decay of okra at 50–80% was presented in no room cooling plus covering with either thermal insulation material or P-LLDPE. The okra pods turned black with mold infection. The DH4 and DH5 treatments had the lowest percentage of ID (<20%) compared to the other four treatments (Figures 3.8 and 3.9). Thermal insulation materials maintained cool temperature and RH (Figures 3.3 and 3.6). This was related to a lower incidence of decay (Figure 3.8) and mass loss (Figure 3.7). Increasing efficiency of thermal insulation covers suggested application with room cooling to maintain a cool temperature under heat stress conditions. However, the application of MFS covering should be considered in case of a high-temperature condition (30 °C) over 15 h, which may lead to heat accumulation (Figure 3.4). Vapor condensation resulted in an increase of okra decay (Figure 3.8) due to low WVP (Table 3.2). Thermal insulation covers may be applied for a short journey (< 6 h) for domestic transportation under ambient temperature (no refrigerated vehicle) to maintain cool temperature with less decay. HRS + TNNW covering with cooling technique showed high potential application for fresh produce with high respiration rates, such as asparagus, broccoli, mushroom, and sweet corn [29]. The overall post-harvest loss from mass loss and incidence of decay showed that TP was the highest post-harvest loss

(65%), followed by DH1 (59%), DH3 (52%), DH5 (27%), DH2 (26%), and DH4 (15%), respectively (Figures 3.7 and 3.8).

Note Six treatments were no room cooling with P-LLDPE covering (TP as control), room cooling with P-LLDPE covering (DH1), no room cooling with HRS + TNNW covering (DH2), no room cooling with MFS covering (DH3), room cooling with HRS + TNNW covering (DH4), room cooling with MFS covering (DH5)

Figure 3.9 Okra Pictures from the Six Treatments including TP (A), DH1 (B), DH2 (C), DH3 (D), DH4 (E), and DH5 (F) after Simulated Storage at 18 °C for 48 h and Simulated Transportation at 30 °C for 15 h

3.4 Conclusions

Room cooling with TNNW provided greater efficiency to preserve a cool temperature (2 °C) and reduce the decay of okra (10%), compared to TP (42%) and no room cooling plus MFS (48%) after simulated cool storage and high-temperature transportation conditions. Application of thermal insulation materials for covering reduced mass loss (5%), compared to either no cover or P-LLDPE throughout the simulation test (15–17%). Thus, the room cooling combined with HRS + TNNW (DH4) gave the lowest post-harvest loss (15%) as compared to TP, cooling plus P-LLDPE (DH1), and no cooling plus MFS (DH3) in a range of post-harvest loss (52% to 65%).

Results showed that cooling was a very important step to apply in the post-harvest handling of okra before covering to remove both field heat and respiratory heat. Material properties, including low thermal heat energy (Q_x) level and high R-value and WVP value, should be considered for developing thermal insulation material for fresh produce. Future research should be conducted to assess the effect of room cooling and thermal insulation material for other fresh fruits and vegetables, particularly the high respiration rate group.

Author Contributions

J.R. conducted experiments, analyzed data, interpreted results, and assisted manuscript writing. R.S. co-investigated, interpreted results, and assisted data analysis. C.P. co-investigated, sup-ported cover materials, interpreted results in material analysis, and assisted manuscript writing. H.K. provided comments and suggestions for the final draft of the manuscript. S.C. was the principal investigator of the research, responsible for the overall research management, interpretation of results, and manuscript writing. All authors have read and agreed to the published version of the manuscript.

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Not applicable.

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Conflicts of interest

The authors declare no conflict of interest.

References

[1] Tripathi, K. K., Warrier, R., Govila, O. P., & Ahuja, V. (2011). Biology of *Abelmoschus esculentus* L. (okra). *Series of Crop Specific Biology Documents*. New Delhi, India: Ministry of Environment and Forests Government of India.

[2] Thai Customs. (2020). *Statistic report 2020*. Retrieved August 12, 2020, from http://www.customs.go.th/statistic_report.php?lang=en&tariff_code=07099990003

[3] Tsado, E. K. (2015). Quality of postharvest handling of marketable okra fruits sold in Minna, Niger state, Nigeria. *European Journal of Agriculture and Forestry Research, 3*(5), 33-45.

[4] *Okra: Postharvest Care and Market Preparation*. (2003). Retrieved November 10, 2020, from http://agriculture.gov.gy/wp-content/uploads/2016/01/Okra.pdf

[5] Perkins-Veazie, P., & Collins, J. K. (1992). Cultivar, packaging, and storage temperature differences in postharvest shelf life of okra. *HortTechnology, 2*(3), 350-352.

[6] Taain, D. A., Jasim, A. M., & Al-Hij, M. J. H. H. (2014). A study of storage behavior of okra fruits (*Abelmoschus esculuntus* L. Moenth cv. Khnesri). *International Journal of Farming and Allied Science, 3*(7), 760-766.

[7] *Okra: The Commercial Storage of Fruits. Vegetables and Florist and Nursery Stocks*. (2016). Retrieved November 10, 2020, from https://www.ars.usda.gov/arsuserfiles/oc/np/commercialstorage/commercialstorage.pdf

[8] Cheng, Z., Gong, X., Jing, W., Peng, Z., & Li, J. (2018). Quality Change of Postharvest Okra at Different Storage Temperatures. *Journal of Food Engineering and Technology, 7*(1), 43-43. doi: 10.32732/jfet

[9] Kader, A. A. (2002). *Postharvest Technology of Horticultural Crops* (3rd ed., pp. 39-47). California: University of California, Davis.

[10] Huang, S., Li, T., Jiang, G., Xie, W., . . . Duan, X. (2012). 1-Methylcyclopropene reduces chilling injury of harvested okra (*Hibiscus esculentus* L.) pods. *Scientia Horticulturae*, *141*, 42-46. https://doi.org/10.1016/j.scienta.2012.04.016

[11] Saltviet, M. E. (2015). *Measuring Respiration*. Retrieved November 10, 2020, from http://ucce.ucdavis.edu/files /datastore/234-20.pdf

[12] Kienholz, J., & Edeogu, I. (2002). *Fresh fruit & vegetable pre-cooling for market gardeners in Alberta*. Retrieved November 10, 2020, from https://open.alberta.ca/dataset/b5b1b32a-6535-4eb0-bed2-663c4b8d4ac4/resource/03ee7373-6d50-41e6-b542-e8a0323c1e68/download/2002-736-14.pdf

[13] Food and Agriculture Organization. (2012). *Good practice in the design management and operation of a fresh produce packing-house*. Retrieved September 9, 2021, from https://www.fao.org/3/i2678e/i2678e00.pdf

[14] Dhall, R. K., Sharma, S. R., & Mahajan, B. V. C. (2014). Development of post-harvest protocol of okra for export marketing. *Journal of Food Science and Technology*, *51*(8), 1622-1625.

[15] Yang, Z., Ma, Z., Zhao, C., & Chen, Y. (2007). Study on forced-air pre-cooling of longan. In *2007 ASAE Annual Meeting* (p. 1). Michigan: American Society of Agricultural and Biological Engineers.

[16] Wang, Z., Chen, L., Yang, H., & Wang, A. (2015). Effect of exogenous glycine betaine on qualities of button mushrooms (*Agaricus bisporus*) during postharvest storage. *European Food Research and Technology*, *240*(1), 41-48.

[17] Deshmukh, G., Birwal, P., Datir, R., & Patel, S. (2017). Thermal insulation materials: A tool for energy conservation. *Journal of Food Processing & Technology*, *8*(04), 1-5. doi: 10.4172/2157-7110.1000670

[18] Wheeler, L., Kitinoja, L., & Barrett, D. M. (2015). Use of insulated covers over product crates to reduce losses in amaranth during shipping delays. *Agriculture*, *5*(4), 1204-1223. doi: 10.3390/agriculture5041204

[19] Singh, S. P., Burgess, G., & Singh, J. (2008). Performance comparison of thermal insulated packaging boxes, bags and refrigerants for single-parcel shipments. *Packaging Technology and Science: An International Journal*, *21*(1), 25-35. doi: 10.1002/pts.773

[20] Harding, K. G. (2018). *Heat Transfer Introduction*. Retrieved September 9, 2021, from https://www.researchgate.net/publication/323144799_Heat_transfer_introduction

[21] Harvey, B. V. (2006). *Mild chilling injury of banana (Cavendish cv. Williams) and its control in the field*. Doctoral dissertation. The University of Adelaide, Adelaide.

[22] Desjarlais, A. O., & Zarr, R. R. (Eds.). (2002). *Insulation materials, testing and applications* (Vol. 1426). Pennsylvania: ASTM International.

[23] Chaiwong, S., & Bishop, C. F. H. (2015). Use of an insulated bag from the supermarket to maintain ‘Elsanta’ strawberry temperature to households. *Acta Horticulturae, 1079,* 187–192. doi: 10.17660/ActaHortic.2015.1079

[24] Melis, R. B. (2016). *New techniques and methods for cold chain monitoring and tracking in perishable products*. Doctoral dissertation. Universidad Politécnica de Madrid, Madrid.

[25] Liu, Y. B. (2011). Low-temperature phosphine fumigation of chilled lettuce under insulated cover for postharvest control of western flower thrips, *Frankliniella occidentalis* (Pergande) (Thysanoptera: Thripidae). *Journal of Asia-Pacific Entomology, 14*(3), 323-325. doi: 10.1016/j.aspen.2011.02.003

[26] American Society for Testing and Materials (ASTM). (2005). *Standard Test Methods for Water Vapor Transmission of Materials (ASTM E96)*. Pennsylvania: ASTM International.

[27] American Society for Testing and Materials (ASTM). (1996). *Standard Test Method for Air Permeability of Textile Fabrics; D737-96*. Pennsylvania: ASTM International.

[28] Kader, A. A., & Saltveit, M. E. (2003). Respiration and gas exchange. In J. A. Bartz & J. K. Brecht (Eds.), *Postharvest Physiology and Pathology of Vegetables* (2nd ed., pp. 7–29). New York: Marcel Dekker Inc.

[29] Patel, B. B., Roy, F. S., Saiyad, M. J. S., & Joshi, D. C. (2016). Respiration behaviour and heat of respiration of mango (cv. Langdo) under different storage conditions. *International Journal of Agriculture, Environment and Biotechnology*, *9*(5), 855-859. doi: 10.5958/2230-732X.2016.00110

[30] Ngure, J. W., Aguyoh, J. N., & Gaoquiong, L. (2009). Interactive effects of packaging and storage temperatures on the shelf-life of okra. *ARPN Journal of Agricultural and Biological Science, 4*(3), 44-49.

[31] Mangaraj, S., Goswami, T. K., & Panda, D. K. (2015). Modeling of gas transmission properties of polymeric films used for MA packaging of fruits. *Journal of Food Science and Technology, 52*(9), 5456-5469.

[32] Tripathi, P. C., & Lawande, K. E. (2010). Temperature-related changes in respiration and Q_{10} coefficient in different varieties of onion. *Progressive Horticulture, 42*(1), 88-90.

[33] Murata, S., Miyauchi, K., & Wang, Y. (1993). Measurement of respiration of fresh vegetables. *Journal of the Japanese Society of Agricultural Machinery, 55*(2), 69-75.

[34] Yasunaga, E., Tomita, K., Hamanaka, D., Hu, W., & Uchino, T. (2001). Effect of temperature on the respiration rate of some vegetables. *IFAC Proceedings Volumes, 34*(28), 205-210.

[35] Bycroft, B. L., Brash, D. W., & Bollen, F. (1996). Using insulation and cooling to improve the asparagus cool chain. *Acta Horticulturae, 415*, 323–332. doi: 10.17660/ActaHortic.1996.415.46

[36] Paternoster, A., Van Camp, J., Vanlanduit, S., Weeren, A., . . . Braet, J. (2017). The performance of beer packaging: Vibration damping and thermal insulation. *Food Packaging and Shelf Life, 11*, 91-97.

[37] Dieckmann, E., Nagy, B., Yiakoumetti, K., Sheldrick, L., & Cheeseman, C. (2019). Thermal insulation packaging for cold-chain deliveries made from feathers. *Food Packaging and Shelf Life, 21*, 100360. doi: 10.1016/j.fpsl.2019. 100360

[38] Lim, B. S., Lim, C. I., & Gross, K. C. (2005). High RH under Pallet Coverage Maintained 'Niitaka'Pear Fruit (*Pyrus pyrifolia Nakai*) Quality during Low Temperature Storage. *Korean Journal of Horticultural Science and Technology, 23*(2), 135-139.

[39] Macnish, A. J., Padda, M. S., Pupin, F., Tsouvaltzis, P. I., . . . Mitcham, E. J. (2012). Comparison of pallet cover systems to maintain strawberry fruit quality during transport. *HortTechnology, 22*(4), 493-501. doi: 10.21273/ HORTTECH.22.4.493

[40] Moureh, J., Laguerre, O., Flick, D., & Commere, B. (2002). Analysis of use of insulating pallet covers for shipping heat-sensitive foodstuffs in ambient conditions. *Computers and Electronics in Agriculture, 34*(1-3), 89-109.

[41] Badia-Melis, R., Mc Carthy, U., Ruiz-Garcia, L., Garcia-Hierro, J., & Villalba, J. R. (2018). New trends in cold chain monitoring applications-A review. *Food Control*, *86*, 170-182.

CHAPTER 4

PERFORMANCE OF THERMAL INSULATION COVERING MATERIALS TO REDUCE POSTHARVEST LOSSES IN OKRA[2]

Abstract

The efficiency of different thermal insulation covers in minimizing temperature fluctuations in cool chain management was investigated to reduce postharvest loss and maintain okra quality during storage and transportation. The four thermal insulation covering materials: (1) heat reflective sheet with thin nonwoven (HRS + TNNW), (2) heat reflective sheet with thick nonwoven (HRS + TKNW), (3) metalized Tyvek® (MTyvek) and (4) metalized foam sheet (MFS) were studied and compared with perforated linear low-density polyethylene (P-LLDPE) as the typical handing package for okra distribution alongside no covering as the control. The material properties, transpiration rate, vital heat, temperature profiles (air and pulp temperatures), relative humidity, mass loss and incidence of decay were determined throughout a simulated supply chain. Results exhibited that HRS + TNNW and HRS + TKNW covers had the lowest thermal heat energy (Q_x) and moderate R-value. These two covers maintained

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low temperature fluctuation with the lowest rate of air and pulp temperature changes, reflecting in lowest mass loss and decay in okra. The HRS + TNNW cover yielded less decay (1%) in okra, compared to commercial covers; MTyvek (16%) and MFS (9%). Results showed that HRS + TNNW exhibited great potential as a thermal insulation cover to reduce postharvest loss in okra (5%) compared to typical handling (11–18%) and could be considered as alternative material to reduce the use of foam sheets in cool chain management distribution packaging of okra under ambient environment conditions.

Keyword: Cool chain management/Covering material/Metalized foam sheet/ Nonwoven

4.1 Introduction

Okra (*Abelmoschus esculentus* L.) belongs to the Abelmoschus genus of the Malvaceae family [1]. Okra is an economic vegetable crop grown in Thailand and exported to global markets, especially Japan, Hong Kong, Switzerland, Germany and the United Arab Emirates. Japan is the main importer of fresh okra from Thailand (worth ap-proximately 5.50 million USD) per annum and accounts for 82.6% of the total exported okra volume [2]. Concerns in okra production, including fruit quality determination, inadequate harvesting procedures, okra harvester training levels, lack of suitable transportation and insufficient pre-cooling facilities, have all been cited as problems for marketable okra [3].

Optimal storage conditions of okra to extend shelf-life from 7 to 10 days ranged from 7 to 10 °C with RH 95 to 100% [4]. Higher temperature at 25 °C resulted in unmarketable quality and shorter shelf-life of 3 days [5-7]. At high temperature, okra is susceptible to water loss, color fading and rotting with loss of commercial value [8]. Okra has a high respiration rate; therefore, temperature is the most significant environmental factor affecting postharvest quality. Increase in storage temperature to 25-27 °C resulted in an elevated respiration rate (328-362 mg CO_2 kg^{-1} h^{-1}) compared with a lower temperature storage at 4-5 °C (53-95 mg CO_2 kg^{-1} h^{-1}) [4]. Mass losses of

okra at 5 °C, 10 °C and 25 °C after 5 days storage were 10%, 16% and 27%, respectively [5].

Cool chain management is a temperature-control process from end-to-end to pre-serve quality of commodities throughout the supply chain [9]. Cool chain management prevents biological decay and ensures delivery of healthy, high-quality food to customers. The optimal storage temperature range for fruits and vegetables is 0 to 16 °C [10]. Several studies have investigated cooling and storage cold chain management of okra [4-5, 7, 11-13]. For heat removal after harvesting, forced-air cooling was recommended for the handling of exported okra [14]. In India, room cooling at 15 °C was applied to exported okra before storage at 8 °C [15]. Recently, room cooling at 0 °C for 2 h was applied in combined with usage of thermal insulation covering materials, to reduce decay incidence and mass loss of okra in Thailand [16].

Material properties including thickness, number of surfaces and number of reflective surfaces are important factors that determine insulating ability of the materials [17]. The most common thermal insulation materials used for pallet cover applications such as polystyrene, aluminum foil and nonwoven fabrics were described in terms of material properties, particularly thermal conductivity. A lower thermal conductivity that restricted heat transfer provided improved thermal insulation property [18]. Polystyrene foam and polyurethane have the lowest thermal conductivity of the possible materials used, followed by nonwoven fabrics or polypropylene. Aluminum foil is a reflective insulation material composed of one or more low-emission surfaces that pro-vides high thermal conductivity and reflects heat to effectively minimize heat radiation [19]. Aluminum foil as pallet cover material is used on its own and combined with expanded polyethylene (EPE) as foam sheet for fresh produce covering [20].

Thermal insulation packaging minimizes the rate of temperature change and is used for up to 50% of chilled food [21]. Investigations have been extensively under-taken on thermally insulated packaging boxes for food delivery and pallet covers for fresh produce during distribution and transportation [18, 20, 22-23]. Pallet covers are used as packaging to minimize waste from food spoilage by delaying rapid changes of temperature and humidity in amaranth [20], chard, cucumber, carrot [22], and straw-berry [23]. However, limited studies have addressed the positive impacts of pallet covers in reducing postharvest loss of fresh fruits and vegetables. Previous research

studies have addressed thermal insulation covering of fresh fruits and vegetables, but no reports are available for okra or other high respiration rate crops. Most previous studies of thermal insulation coverings on fresh produce only focused on controlling temperature, with no examination of fresh produce quality. Recently, the first report on thermal insulation packaging of fresh produce was done to evaluate efficiency of thermal insulation covering materials combined with room cooling for controlling temperature fluctuation and reduction of postharvest mass loss and decay of okra. Results suggested that room cooling at 0 °C for 2 h for heat removal was important before covering with thermal insulation materials. Combined room cooling with two-layer heat reflective sheet with thin nonwoven (HRS+TNNW) as a developing handling exhibited the highest efficiency for preserving cool temperature and reducing postharvest loss of okra (mass loss and decay) (15%) compared to typical handling (no room cooling and covering) (65%), covering with perforated linear low-density poly-ethylene (59%) and metalized foam sheet (MFS) (27%). Furthermore, the difference in postharvest loss between no room cooling and room cooling observed in HRS+TNNW and MFS treatments were 11% and 25%, respectively. This indicated that room cooling plays an important role in maintaining the okra quality as a pretreatment before covering with thermal insulation material [16].

According to domestic transportation of okra from community enterprise in Phayao province (in the northern part of Thailand) to food factories (in the central part of Thailand), high temperature and relative humidity fluctuations in transportation vehicles caused postharvest losses of okra such as wilting heat damage and decay. Poor cooling facilities, including no pre-cooling, no cooling storage and non-refrigerated vehicle during transportation, all caused physiological loss. Losses of perishable crops due to a lack of refrigeration were higher in developing countries (23%) than in developed countries (9%) [24]. In this study, a prototype of thermal insulation covering was designed by combining materials between heat reflective sheet and thin nonwoven (HRS + TNNW) as an alternative to foam-based material to minimize okra postharvest losses and transportation cost. The objectives of this study were: (1) to investigate the performance of different thermal insulation covering materials in controlling temperature fluctuations under storage and transportation temperature conditions, and

(2) to evaluate the reduction of postharvest loss and the quality of okra, when covered with thermal insulation materials.

4.2 Material and Methods

4.2.1 Determination of Material Properties

Thermal insulation materials employed for covers were perforated linear low-density polyethylene (P-LLDPE), thin nonwoven (TNNW), thick nonwoven (TKNW), heat reflective sheet (HRS), metalized Tyvek® (MTyvek) and metalized foam sheet (MFS). Their thermal properties as rate of heat energy (Q_x), R-value, water vapor permeability (WVP) and air permeability were determined. Six replicates were tested and average values were reported.

Equipment settings and thermal heat energy measurements were performed following the procedure of Harvey [25] and our previous research [16]. Briefly, rate of thermal heat energy (Q_x) was determined as the rate at which heat energy passed through the material by using two expanded polystyrene (EPS) boxes with a hole (10 × 10 cm^2) between two chambers. Temperature data loggers (Tinytag Talk 2: TK-4014-PK, Gemini Data Loggers, Chichester, West Sussex, UK) were used to monitor the temperature change between the two chambers for 3 h until constant, and the transfer rate of thermal heat energy (Q_x) in J s^{-1} unit was calculated.

Water vapor permeability (WVP) was examined for different insulation materials using the desiccant in cup method. Following ASTM96 [26], the specimen or cover material (20 cm^2) was sealed to the open mouth of a test dish containing a desiccant and placed in a constant climate chamber (KBF-115, Binder, Tuttlingen, Germany) at 25 °C with 50% RH. WVP was calculated as rate of water vapor transmission in g h^{-1} m^{-2} unit. Air permeability was determined using an air permeability tester (FX 3300 LabAir IV, Textest Instruments, Schwerzenbach, Switzerland) according to ASTM D737-04 [27]. The thermal insulation materials were cut into 20 × 20 cm^2 squares and results were reported in L m^{-2} s^{-1} unit.

The R-value was calculated as resistance to heat flow through the thermal insulation material using the ice-melt procedure of Singh et al. [18]. To calculate the melt rate, the weight of water was reported as m^2 °C W^{-1} unit using equation.

System R-value = (Surface area × Temperature difference)/ (Melt rate × Latent heat)

where, surface area is inside surface area of the thermal insulation cover (m^2), temperature difference (°C) is ambient temperature − melting point of ice (25 °C – 0 °C = 25 °C), melt rate (kg h^{-1}) is weight of water collected divided by test time, latent heat is 335 kJ kg^{-1}.

4.2.2 Plant Materials and Treatments

'Lady Finger' okra pods were harvested around 45 days after planting or 6 days after flowering (September 2019) from the okra plantation (latitude 20°13'27.2"N longitude 99°50'05.2"E) in Mae Chan district, Chiang Rai Province. The okra pods (5 kg) were carefully transferred into 10 kg plastic baskets to protect against bruising or abrasion from the farm to the Postharvest Laboratory (S7) at Mae Fah Luang University within 30 min. After arrival at the laboratory, okra pods were graded for size uniformity with pod length of 7 to 11 cm (specific size for okra processing) and sorted according to minimum requirements; fresh, green in color, free distinct signs of bruising, smooth and clean at pedicel cut surface. The okra pods (1,500 g) were packed in plastic baskets for room cooling treatment for 2 h by setting the cooling medium at 0 °C. The pulp temperature of okra was monitored, using a multichannel data logger (Hioki, LR8431, Nagano, Japan) connected with a type-K thermocouple for 10 channels (plastic baskets), to check uniformity of pulp temperature during room cooling treatment. The final pulp temperature of packed okra in all baskets reached 9 °C after room cooling for 2 h. After cooling, the okra pods were packed in six treatments of different insulation materials (four treatments and P-LLDPE), including no cover as a control.

Six treatments included five covering materials; P-LLDPE, HRS+TNNW, HRS+TKNW, MTyvek and MFS (Figure 4.1) with size of 18 × 32 × 12 cm^3, compared with control (no cover). The HRS material was evenly perforated with a pin of diameter 0.55 mm to give total perforation area of 0.09 cm^2. Two layers of covers as HRS+TNNW and HRS+TKNW were prepared by attaching HRS and NW via spot

bonding (Figure 4.2). Following the postharvest handling of okra from community enterprise in Phayao province, all six treatments were transferred to simulated storage at 18 ± 2 °C for 48 h, followed by simulated transportation. at 30 ± 1 °C for 15 h.

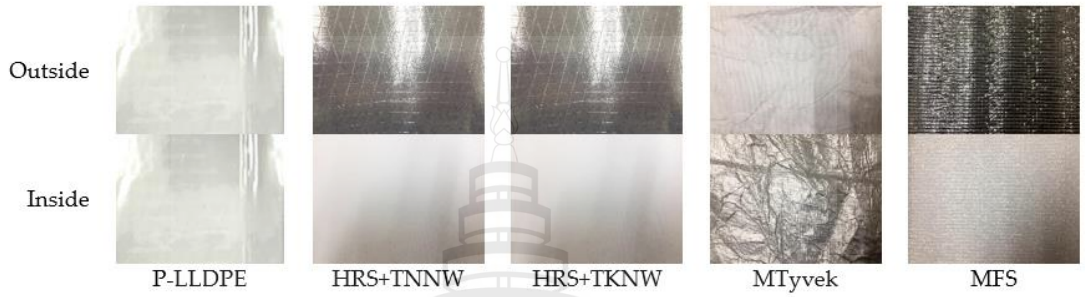


Figure 4.1 Five Insulation Materials as Treatments

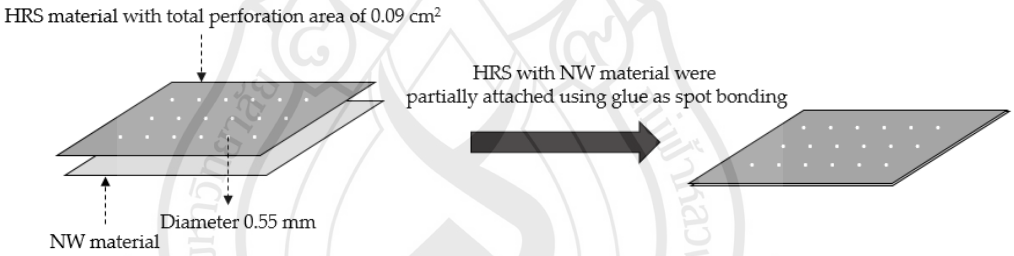


Figure 4.2 Function Design of the Combination between HRS and NW Materials

4.2.3 Determination of Air and Pulp Temperature in Okra

Air and pulp temperatures inside the okra pod were measured at 30 s intervals from the start of cooling using two types of temperature data loggers; air temperature (Tinytag Talk 2: TK-4014-PK, Gemini Data Loggers, Chichester, West Sussex, UK) with three replicates and pulp temperature (Tinytag Talk 2: TK-4023-PK, Gemini Data Loggers, West Sussex, UK) with four replicates. Percentage RH level was determined by a temperature and RH data logger (Tinytag Ultra 2: TGU-4500, Gemini Data Loggers, Chichester, West Sussex, UK) at intervals of 30 s.

Measured air and pulp temperatures were analyzed using a boxplot at 12 h after simulated storage and transportation. Rates of temperature changes (°C h^{-1}) during temperature rise after cooling to 25 °C for temperature ranges of 25 °C to 30 °C were calculated. Median value temperatures were presented as boxplots and included accumulated time-temperature (ATT) (°C h) throughout the simulated supply chain. Heatmap analyses representing air and pulp temperature levels during 12 h after simulated storage and transportation were presented. Heatmap visualizations were created using MATLAB Software version R2018a (MathWorks Inc., Natick, MA, USA) in this study.

For thermal imaging, temperatures were immediately recorded by a thermal camera (FLIR ONE®, Pro LT, Teledyne FLIR, Wilsonville, OR, USA) after removing the cover to provide a rapid visual comparison at the end of simulated transportation.

4.2.4 Determination of Respiration Rate and Vital Heat

In a closed system, the rate of okra respiration was measured, as shown in Figure 4.3. The detail in test set up was described elsewhere in our previous study [16]. Briefly, the okra pods (150 g) were packed in a plastic food container (8400 mL) under three storage temperature conditions (10, 20, 30 °C) with a range of 70-90% RH. Gas was sampled for CO_2 detection at day 2 (48 h) and day 3 (72 h) and analyzed by a gas chromatograph (GC) (7890A, Agilent Technologies, Santa Clara, CA, USA). Respiration rate (R_c) for respiration was calculated to unit of mL CO_2 kg^{-1} h^{-1} and converted to mg CO_2 kg^{-1} h^{-1} by multiplying conversion figure at 10 °C (1.89), 20 °C (1.83) and 30 °C (1.77) [28-29]. The temperature coefficient (Q_{10}) was calculated [30].

$$R_c\,(\text{mg } CO_2\ kg^{-1}\ h^{-1}) = (\%CO_2 \times V) / (100 \times FW \times T)$$

where, CO_2 is the concentration of CO_2 gas (%), V is volume of container (mL), FW is fruit weight (kg) and T = closing time (h).

$$Q_{10} = (R_2/R_1)^{10/(T_2 - T_1)}$$

where, R_2 and R_1 are the respiration rate at temperature T_2 and T_1, respectively.

The calculated Q_{10} values on day 2 (48 h) and day 3 (72 h) (Table 4.1) were then employed to estimate the respiration rate of okra pods (R_e) at various air temperature levels inside different covers and no cover. Air temperatures in either covers or no cover were recorded using a temperature data logger (Tinytag Talk 2: TK-4014-PK, Gemini Data Loggers, Chichester, West Sussex, UK) under simulated storage (18 °C for 48 h) and transportation (30 °C for 15 h) temperature conditions. The air temperature level for estimation of okra respiration rate (R_e) in each cover treatment was determined from the median air temperature after simulated storage and transportation (Section 4.2.3). Respiration rates (R_c) at 20 °C after 48 h and at 30 °C after 72 h were used to estimate okra respiration rate under simulated storage and transportation (Section 4.2.3). Estimated respiration rates of okra among treatments were calculated.

$$R_e = R_c \times Q_{10}^{(T_2 - T_1)/10}$$

where, R_e is the estimated respiration rate of okra in each cover or no cover, R_c is the respiration rate from closed system, T_2 is the final air temperature after simulation, and T_1 is the initial air temperature before simulation.

Table 4.1 Okra Respiration Rate in a Closed System after Three Storage Conditions at (10, 20 and 30 °C) for 2 and 3 Days

Temperature	**R_c (mg CO_2 kg^{-1} h^{-1})**		**Q_{10}**	
(°C)	**Day 2**	**Day 3**	**Day 2**	**Day 3**
10	183.33	195.26		
			1.40	1.51
20	245.11	276.68		
			1.37	1.46
30	333.15	399.05		

A heat production (2.55 cal) from respiration is calculated by a CO_2 production of 1 mg. A respiration rate of 1 mg CO_2 kg^{-1} h^{-1} indicates a heat production of 61.2 kcal ton^{-1} day^{-1}. In this study, vital heat from respiration of okra was calculated and converted into a unit of J kg^{-1} h^{-1} from kcal ton^{-1} day^{-1} [31].

$$\text{Vital heat (J kg}^{-1}\text{ h}^{-1}\text{)} = R_e \times 10.7$$

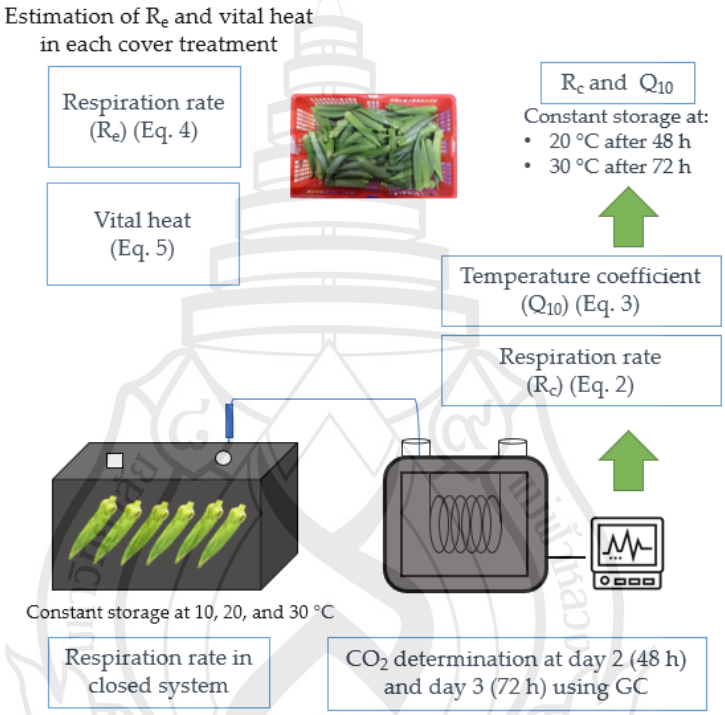


Figure 4.3 Determination of Respiration Rate and Vital Heat

4.2.5 Determination of Transpiration Rate

The transpiration rate was calculated from the mass of okra pods using an electric weighing balance (Pioneer TM, Ohaus, Parsippany, NJ, USA). Initial mass before cooling and final mass at the end of storage simulation (18 °C for 48 h) and transport simulation (30 °C for 15 h) were determined. Transpiration rate was calculated per unit of surface area (TR_A) in g h^{-1} m^{-2} [32].

$$TR_A = (m_i - m_t)/ (t \times A)$$

where, mi is the initial fruit mass (g), mt is the mass of fruit at time (g), t is time (h) and A is the surface area of the fruit (m^2).

Surface area of the okra pod was calculated [33].

$$S = \pi D_g^2$$

where, S is surface area (m^2) and D_g is geometric mean.

The geometric mean of okra was estimated calculation for the cylindrical nature of okra pod shape (Figure 4.4) [33].

$$D_g = \sqrt[3]{L \times W^2}$$

where, L is length (m) and W is width (m).

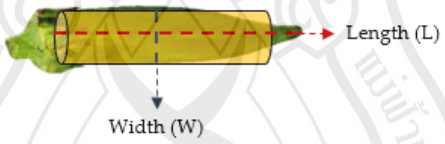


Figure 4.4 Geometry of Okra Pod Shape

4.2.6 Mass Loss Determination

Mass loss of okra pods was determined using an electric weighing balance (Pioneer ™, Ohaus, NJ, USA). Percentage mass loss (%) was calculated on the basis of initial weight (IW) before cooling and final weight (FW) at the end of simulated storage (18 °C for 48 h) and simulated transportation (30 °C for 15 h) by the equation WL (%) = [(IW−FW)/IW] × 100.

4.2.7 Incidence of Decay

The decay of okra pods was described in four categories as <10 % of decay occurrence, 10–25 % of decay occurrence, 25–50 % of decay occurrence and >50 % of decay occurrence. The initial decay symptom exhibited tissue damage containing a

small-soaked lesion or the whole pod covered up with a grayish-white mass of mold. The okra pods of each decay symptom were categorized and weighed (D). The percentage decay (%D) in each category was determined on the basis of total weight per plastic basket of pods after storage at 18 °C for 48 h (TW) using; D (%) = [(D/TW) × 100] [34]. Incidence of decay was determined at the end of simulated transportation.

4.2.8 Statistical Analysis

SPSS for Windows version 20 (SPSS Inc., Chicago, IL, USA) was used for statistical, correlation and cluster analyses. Data analyses for material properties, transpiration rate, vital heat, rate of temperature change, mass loss rate and incidence of decay among the six treatments were compared by mean (α=0.05) using Tukey's HSD test. All data variables among six treatments were analyzed using Pearson correlation analysis at the 0.01 level. Material properties, transpiration rate, vital heat, rate of air and pulp temperature changes, accumulated time-temperature, mass loss and incidence of decay from the six treatments were determined as clustering analysis using Ward's coefficient by agglomerative hierarchical clustering.

4.3 Results and Discussion

4.3.1 Materials Properties

Properties of covering materials including thickness, Q_x, R-value, WVP and air permeability were shown in Table 4.2. P-LLDPE (thickness of 0.120 mm) having low insulation property exhibited the highest thermal heat energy value (Q_x) of 3.750×10^{-4} J s^{-1}, while MFS (thickness of 3.100 mm) with high insulation property exhibited the lowest thermal heat energy (1.440×10^{-4} J s^{-1}). High R-value of material indicates high insulation property that relates to low thermal heat energy value. Highest R-value of MFS was 0.223 m^2 °C W^{-1} followed by HRS (0.214 m^2 °C W^{-1}), MTyvek (0.208 m^2 °C W^{-1}), TKNW (0.194 m^2 °C W^{-1}), TNNW (0.181 m^2 °C W^{-1}) and P-LLDPE (0.161 m^2 °C W^{-1}). Heat transmission played a role in temperature transfer and material property that explained the performance of temperature preservation by material covers [22, 35]. Heat transfer can be defined as the transmission of energy that results in a temperature differential [35]. Thermal heat energy (Q_x) and R-value variables were the

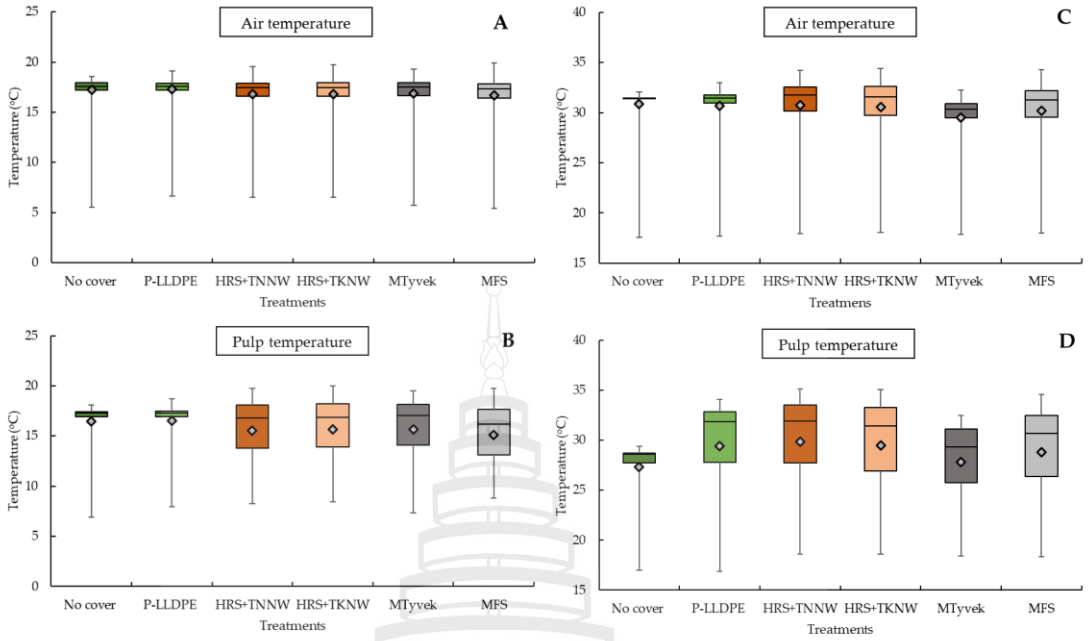
principal thermal insulation qualities in this investigation (Table 4.2). Highest insulation property was observed in MFS that had the lowest thermal heat energy as well as the highest R-value, while MTyvek and HRS materials had lower Q_x and greater R-value levels than the two nonwovens of different thicknesses (TKNW and TNNW). Regarding thermal heat energy (Q_x), lower Q_x level indicated lower heat transfer rate (good insulator) through the material layer [25]. In thermal insulation material applications, the thickness of materials (conduction), the bulk movement of fluids (heat transfer between solid and fluid) (convection) [35], and number of reflective surfaces (radiation) affect the insulating ability [17]. The thermal insulation material prototype was designed as HRS combined with either TNNW (0.270 mm) or TKNW (0.470 mm) to increase insulation property. Developing a thermal insulation material for okra package cover improved more conduction by increasing nonwoven thickness, convection by increasing the number of layer materials and reflective surface by applying HRS with nonwoven material.

In terms of water vapor permeability (WVP), the partial pressure difference between inside and outside of the test material impacts moisture gain or loss in the product [36]. From results, TNNW (0.373 g h^{-1} m^{-2}) and P-LLDPE (0.360 g h^{-1} m^{-2}) provided higher WVP than MFS (0.000008 g h^{-1} m^{-2}) and HRS (0.000002 g h^{-1} m^{-2}) (Table 4.2). Similarly, WVP of LLDPE-based nanocomposite films ranged from 0.07 to 0.31 g h^{-1} m^{-2} [37], and higher than WVP of aluminum foil (0.009 mm) (0.00042 to 0.00051 g h^{-1} m^{-2}) [38]. Using high WVP materials gives potential to eradicate vapor condensation, thus reducing microbial activity [36]. Air permeability through TNNW sheet was the highest (917.000 L m^{-2} s^{-1}), while those through HRS (0.543 L m^{-2} s^{-1}) and MTyvex (0.497 L m^{-2} s^{-1}) were the lowest. MFS and HRS materials had low WVP and air permeability values (Table 4.2), resulting in vapor condensation inside the covers. A designed combination of perforated HRS with either TNNW or TKNW provided good thermal insulation, water and air permeability and highest overall thermal insulation properties to maintain lower air and pulp temperature levels (Figure 4.5) without moisture condensation inside the cover.

Table 4.2 The Properties of Six Covering Materials (thickness, thermal heat energy, WVP, R-value and air permeability)

Material	Thickness (m)	Thermal heat energy ($Q_x \times 10^{-4}$) ($J\ s^{-1}$)	R-value ($m^2\ ^oC\ W^{-1}$)	Water vapor permeability ($g\ h^{-1}\ m^{-2}$)	Air permeability ($L\ m^{-2}\ s^{-1}$)
P-LLDPE	0.131 ± 0.20^{e}	3.750 ± 0.07^{a}	0.161 ± 0.00^{d}	0.360 ± 0.03^{a}	172.801 ± 5.85^{b}
TNNW	0.282 ± 0.10^{d}	3.255 ± 0.04^{b}	0.181 ± 0.00^{c}	0.373 ± 0.11^{a}	917.000 ± 64.27^{a}
TKNW	0.478 ± 0.28^{c}	3.148 ± 0.00^{b}	0.194 ± 0.00^{c}	0.0083 ± 0.00^{b}	168.623 ± 21.70^{b}
HRS	1.445 ± 0.02^{b}	2.368 ± 0.15^{c}	0.214 ± 0.01^{b}	0.000002 ± 0.00^{d}	0.543 ± 0.07^{d}
MTyvek	0.127 ± 0.03^{e}	2.947 ± 0.02^{bc}	0.208 ± 0.00^{b}	0.00057 ± 0.00^{c}	0.497 ± 0.03^{d}
MFS	3.109 ± 0.01^{a}	1.440 ± 0.06^{d}	0.223 ± 0.01^{a}	0.000008 ± 0.00^{d}	45.503 ± 4.20^{c}

Note Different letters indicate significant differences at $p<0.05$ .Values are mean ±S.E.from six replicates



Note The lower and upper quartiles are represented by boxes. The horizontal line represents the median temperature in each box while the mean temperature is indicated by (◊). Minimum and maximum temperatures are presented by vertical lines extending above and below each box

Figure 4.5 Boxplot of Air (A) and Pulp (B) Temperature Profiles during Simulated Storage at 18 °C for 12 h. Air (C) and Pulp (D) Temperature Profiles during Simulated Transportation at 30 °C for 12 h

4.3.2 Temperature and RH Inside Cover Materials

In postharvest handling, application of insulation packaging for fresh produce to preserve cool temperature requires cooling treatment before covering. The efficiency of controlling low temperature was analyzed and presented as a box plot graph (Figure 4.5). The means (rhombus symbol) of air and pulp temperature levels inside HRS+TNNW, HRS+TKNW, MTyvek and MFS treatments (range of pulp temperature (15.5 °C) and range of air temperature (16.8 °C)) during simulated storage at 18 °C for 12 h were lower than both no cover and P-LLDPE treatments (range of pulp temperature (16.5 °C) and range of air temperature (17.2 °C)) (Figure 4.5A). Pulp temperature control with low fluctuation was shown by the large size of boxplot. No

cover and P-LLDPE treatments exhibited a narrow range of cool air temperature (smaller box-plot) compared with the other four thermal insulation covers (HRS+TNNW, HRS+TKNW, MTyvek and MFS) (larger boxplots) under simulated storage (Figures 4.5A, B). During simulated storage at 18 °C for 12 h, lower air and pulp temperature levels observed in these four thermal insulation treatments corresponded to their lower Q_x values and higher R-values, compared to no cover and P-LLDPE treatments (Table 4.2). After transferring to a higher temperature (simulated transportation), MTyvek maintained lower mean air and pulp temperatures (29.5 °C and 27.8 °C) than the other five treatments (no cover at 30.9 °C and 27.3 °C, P-LLDPE at 30.7 °C and 29.5 °C, HRS+TNNW at 30.8 °C and 29.9 °C, HRS+TKNW at 30.5 °C and 29.5 °C and MFS at 30.2 °C and 28.8 °C) as shown in Figure 4.5B and D. In commercial practice, maximum temperature inside Tyvek cover of asparagus reduced by 8-9 °C compared to no cover [39].

In this study, good temperature control during simulated transportation (Figures 4.5C, D) was associated with lower rates of changes in air and pulp temperatures in the four thermal insulation treatments (Table 4.3). The no cover treatment showed the highest rates of air and pulp temperature changes at all conditions (T_1 to 25 °C and 25 °C to 30 °C), compared to P-LLDPE and the four thermal insulation treatments. This indicated that covering with either P-LLDPE or thermal insulation materials reduced temperature changes under both simulation conditions (Table 4.3). These findings further support the idea of Liu [40] study. a typical double-bubble foil insulation sheet with 97% heat reflectance and a very low heat conductivity was applied to phosphine fumigation in chilled lettuce. The average rate of temperature change was 0.173 °C h^{-1}. The rise in temperature was only 2.7 °C at the end of the 18 h fumigation treatment at the start of the fumigation (4.5 °C).

A high rate of temperature change in no cover and P-LLDPE, observed during simulated storage and transportation, was in good agreement with heatmap results that exhibited a matrix of red-blue color tones from 0 to 35 °C during each hour for 12 h testing (Table 4.3 and Figure 4.6). In both simulated storage and transportation conditions, no cover and P-LLDPE treatments exhibited higher air temperature than the other four cover treatments (Figures 4.6A, C), while the other four thermal insulation covers exhibited lower pulp temperature than no cover and P-LLDPE within

6 h for simulated storage (Figure 4.6B). No cover and MTyvek presented a light orange color tone, indicating lower average air and pulp temperatures during simulated 12 h-transportation compared with the other four treatments (Figures 4.6C, D). These heatmap results were corresponding well with results of thermal imaging that illustrated purple tone color (representing a low pulp temperature) after simulated transportation at 30 °C for 15 h (immediate removal covering) (Figure 4.7). This implied that both no cover and MTyvek treatments had higher air ventilation and heat transfer from inside the cover to the environment under simulated transportation. Therefore, the thermal image technique could be considered as an additional rapid technique to monitor the temperature. When temperature assessment is conducted on metalized sheet material, awareness of the camera emissivity setting [22] as well as the impacts of high emissivity coatings and orientation of the readings are important [41].

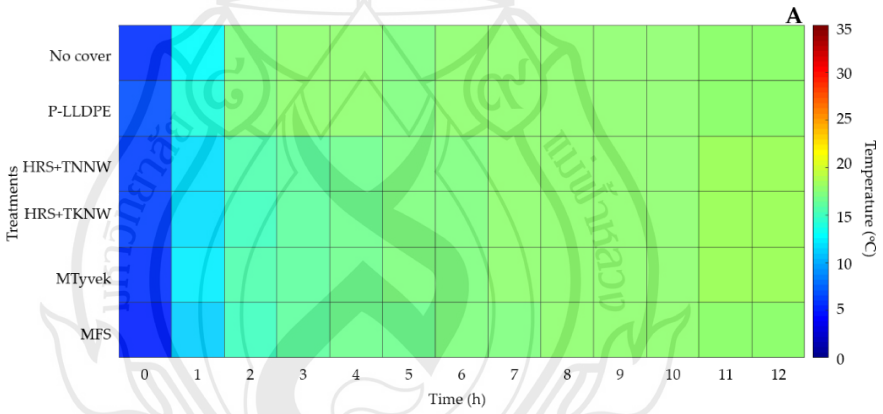


Figure 4.6 Heatmap Chart of Air (A) and Pulp (B) Temperature Profiles during Simulated Storage at 18 °C for 12 h. Air (C) and Pulp (D) Temperature Profiles during Simulated Transportation at 30°C for 12 h

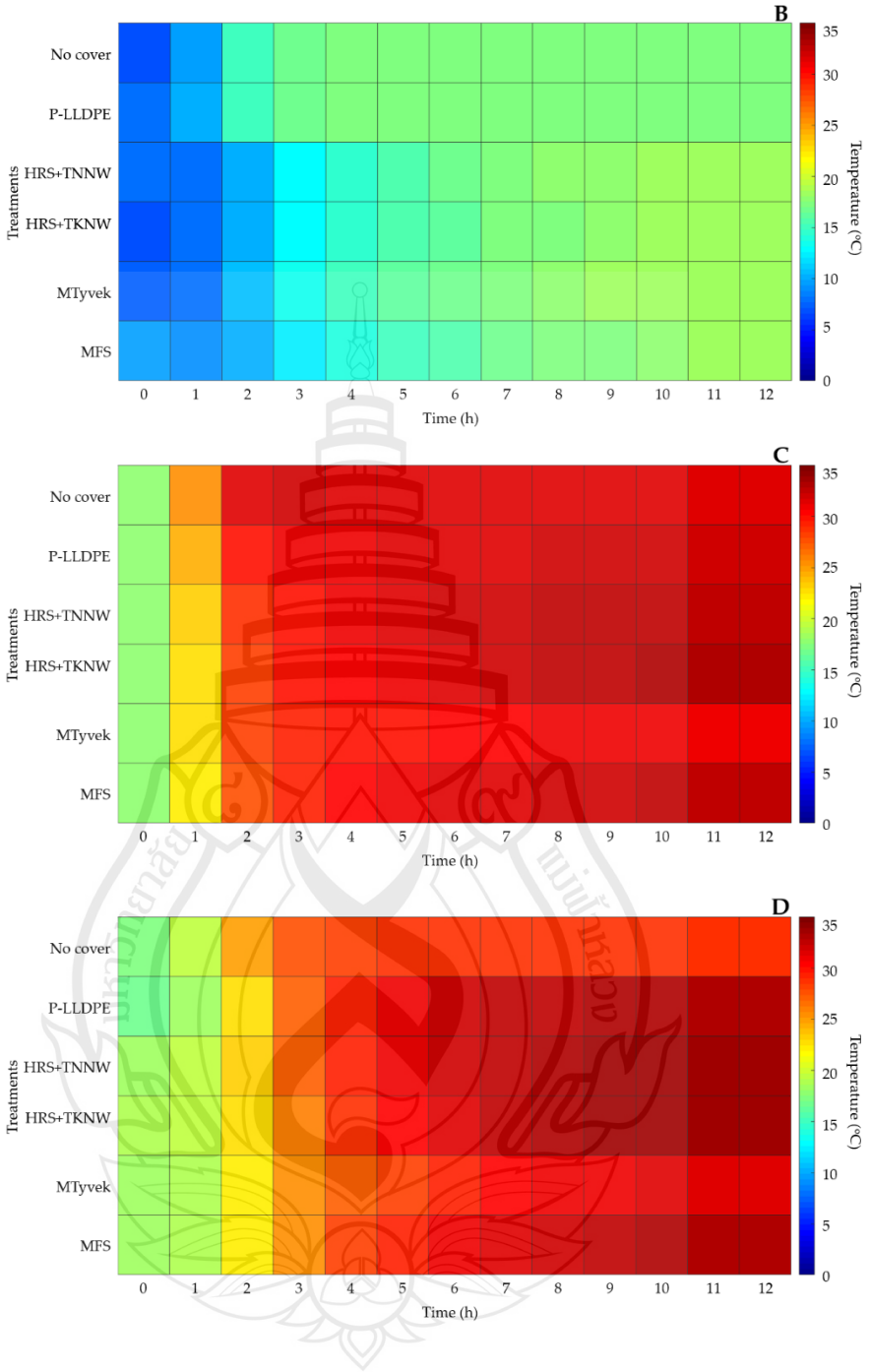


Figure 4.6 (continued)

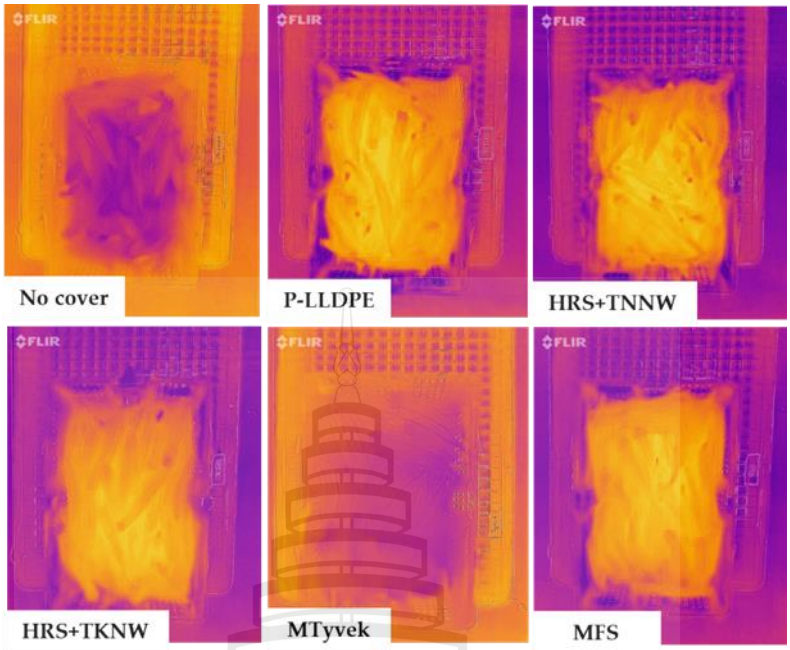
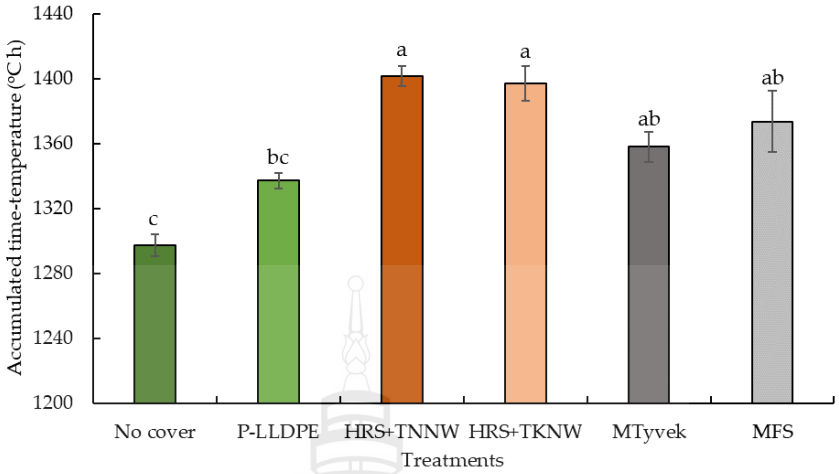


Figure 4.7 Thermal Imaging among the Six Treatments Represented Pulp Temperature after Finishing Simulated Transportation at 30 °C for 15 h (removal covering). Purple and Orange Color Zones Represent Cool and Warm Temperature Gradients, Respectively

HRS+TKNW treatment exhibited the highest accumulated time-temperature (ATT) of 1,396.4 °C h followed by MFS (1373.4 °C h), MTyvek (1357.8 °C h), P-LLDPE (1337.1 °C h) and no cover (1297.0 °C h) (Figure 4.8). The use of thermal insulation covers containing aluminum sheet (HRS+TNNW, HRS+TKNW and MFS) over 7 h resulted in greater heat accumulation inside the cover, caused by the high respiration of okra compared with no cover and P-LLDPE treatments (Figures 4.5-4.7). Similarly, our previous study showed that thermal insulation materials (HRS+TNNW and MFS) tended to build up pulp temperature of okra under simulated transportation at 30 °C for 15 h [16]. This result was consistent with Bycroft et al. [42] who recommended that long-term covering of asparagus should be reconsidered due to higher heat accumulation compared to no cover.



Note Different letters indicate significant differences at $p<0.05$. Values are mean ± S.E. from four replicates

Figure 4.8 Accumulated Time-Temperature (ATT) (°C h) among the Six Treatments after Simulated Storage at 18 °C for 48 h and Simulated Transportation at 30 °C for 15 h

From results, it was suggested that application of a thermal insulation cover for okra (high respiration rate crops) under high temperature (25 °C) should be less than 7 h to avoid increased heat accumulation. Application of frozen gel pack helped to reduce temperature rise of food products (chicken salad and Brie cheese) inside Mylar foil bags under stress temperature at 37 °C [43]. Thus, placement of frozen gel packs is recommended inside thermal insulation covers to maintain low temperature under condition of extremely high temperature. Future study on applying thermal insulation covering in other high respiration rate crops and the use of gel packs or gel phase change materials (PCMs) should also be considered, while investigating the reduction in browning or blackening from mechanical damage under actual or simulated transportation would also be beneficial.

Scant research has been conducted on thermal insulation covers in okra or other high respiration rate crops. This study aimed to evaluate and assess thermal insulation covers in okra as a representative of high respiratory crops. The use of aluminum-based materials in combination with either nonwoven or expanded polyethylene (EPE)

materials focused on developing thermal insulation covers (Table 4.2). Overall results on air and pulp temperatures inside the four thermal insulation covers gave improved performance and maintained low temperature profiles and fluctuation than no cover and P-LLDPE cover treatments (Figures 4.5, 4.6 and 4.8) (Table 4.3). Materials with lower Q_x value and higher R-value exhibited higher efficiency in maintaining low air and pulp temperatures (Table 4.2). Few studies on other fresh produce identified the positive effect of thermal insulation covers in controlling the inside cool temperature. The insulated pallet cover Reflectix^{TM} constructed of aluminum foil and 0.8 cm poly-ethylene/bubble pack reduced mass loss in amaranth with less wilting and retained the desirable dark green leaf color [20], In strawberry, Tyvek®, a flash-spun nonwoven high-density polyethylene maintained cool temperature and prevented quality loss from supermarket to household refrigerator [23]. Insulation pallet coverings (Tyvek®, Metalized PET, Metalized PET bubbles) have provided greater temperature retention compared to no covering in chard, cucumber and carrot [22]. Recently, our previous study showed that application of thermal insulation covering (HRS+TNNW and MFS) in combined with room cooling (17 °C) could maintain the lowest mean pulp temperature, compared to P-LLDPE and no cover (19 °C) under simulated storage at 18 °C for 48 h [16]. Most academic reports revealed that application of different commercial covers yielded greater performance of thermal insulation compared to no cover but only a few studies have compared material function design of different commercial covers. In this study, commercial HRS material was perforated using a pin of diameter 0.55 mm to give total perforation area of 0.09 cm^2. Two layers of either HRS+TNNW and HRS+TKNW were partially attached using glue as spot bonding. These designed insulation materials possessed moderate Q_x and R-value and exhibited good performance in controlling low temperature, heatmap profiles, thermal images and rate of temperature changes compared to commercial MFS that had the lowest Q_x and highest R-value levels (Tables 4.2 and 4.3) (Figures 4.5-4.7).

Table 4.3 Rates of Air and Pulp Temperature Change in Six Treatments under 15 h of Simulated Transportation at 30 °C

Treatment	Rate of temperature change (°C h^{-1})			
	Air temperature		Pulp temperature	
	T_1 to 25 °C	25 °C to 30 °C	T_1 to 25 °C	25 °C to 30 °C
No cover	18.94 ± 1.20^{a}	14.05 ± 2.48^{a}	5.38 ± 0.04^{a}	$3.27 \pm 0.28^{a***}$
P-LLDPE	16.11 ± 1.19^{ab}	4.70 ± 0.44^{b}	4.21 ± 0.24^{b}	2.72 ± 0.15^{ab}
HRS+TNNW	13.35 ± 1.94^{bc}	2.66 ± 0.63^{b}	3.36 ± 0.04^{c}	2.50 ± 0.23^{ab}
HRS+TKNW	11.41 ± 0.14^{bc}	2.17 ± 0.38^{b}	3.02 ± 0.23^{cd}	2.33 ± 0.09^{b}
MTyvek	11.15 ± 1.02^{bc}	1.46 ± 0.30^{b}	2.72 ± 0.05^{d}	1.27 ± 0.13^{c}
MFS	9.26 ± 0.65^{c}	2.17 ± 0.51^{b}	2.91 ± 0.06^{cd}	1.92 ± 0.14^{bc}

Note Different letters indicate significant differences at $p<0.05$. Values are mean ±S.E. from five replicates. *** It is noted that no cover treatment was estimated temperature at 28 °C due to the maximum pulp temperature level at air temperature at 30 °C

Optimal RH for storage of okra at 95 to 100% extended shelf-life by 7 to 10 days [4]. Application of thermal insulation covers reduced RH fluctuation better than no cover throughout simulated storage and transportation conditions. Covering maintained RH level at 100% RH after both simulated conditions for 8 h (Figure 4.9). Stability of RH level under thermal insulation materials was related to low WVP of the materials. Similarly, our previous study found that thermal insulation covering prevented RH fluctuation better than no covering, resulting in the highest RH level at 100% RH [16]. In this study, MFS cover treatment provided the lowest WVP level (Table 4.2). It had been reported that RH level inside Tyvek® cargo cover at 50% RH (high water vapor permeability) was lower than aluminum bubble wrap with 80% RH (lower water vapor permeability) [44]. However, limited academic research has focused on the application of thermal insulation materials for maintaining RH. Lim et al. [45] investigated the effect of RH on the quality of ‘Niitaka’ pears using polyethylene (PE) film pallet covers to maintain high RH in commercial low temperature storage rooms. When opened, the PE pallet cover had a lower RH level (83 to 87%) than when closing

PE (93 to 95% RH), while Wheeler et al. [20] discovered that RH level in clamshells packed in both covered and uncovered pallets increased to almost 100% RH within one hour of storage and remained high throughout the storage duration (6 h).

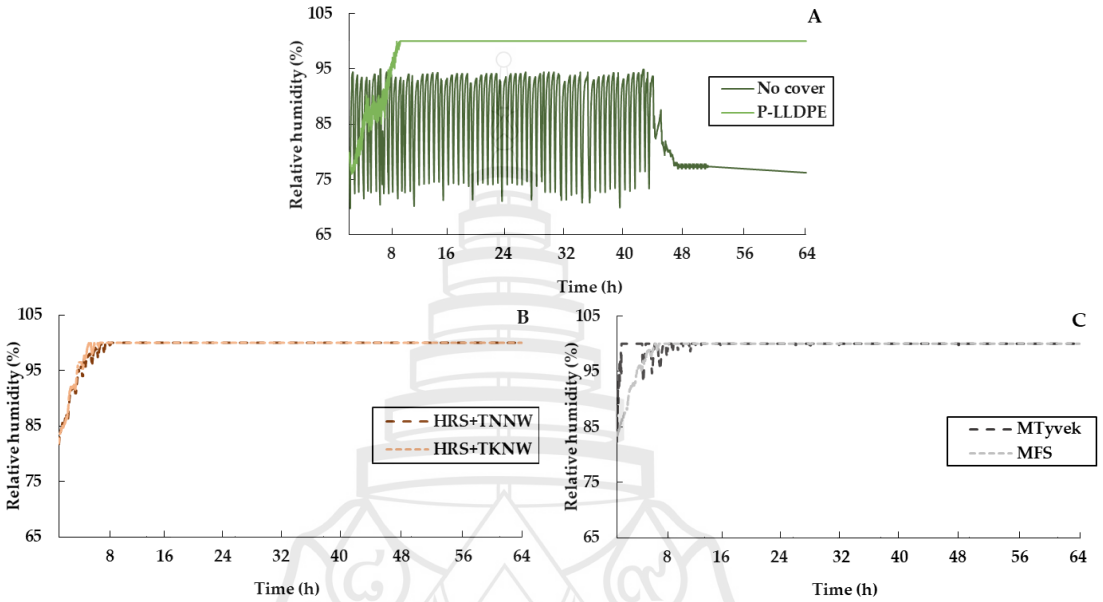


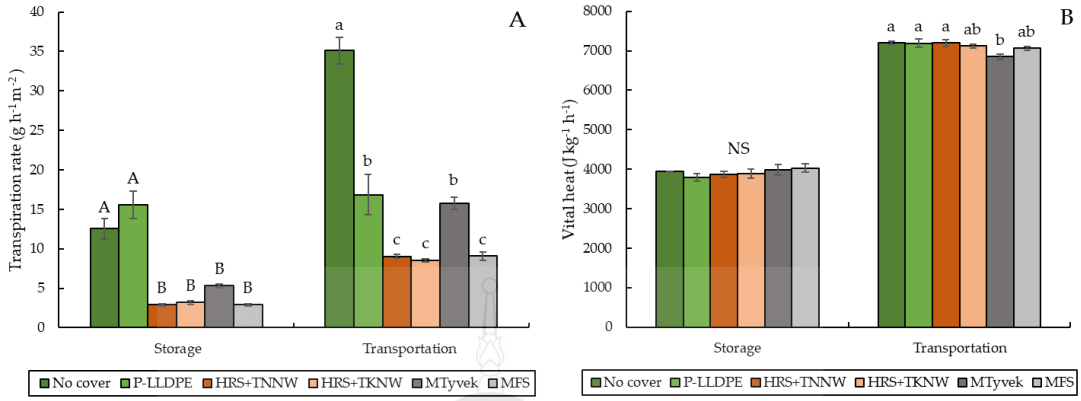
Figure 4.9 RH Profiles among the Six Treatments of No Cover and P-LLDPE (A), HRS+TNNW and HRS+TKNW (B) and MTyvek and MFS (C) after Simulated Storage at 18 °C for 48 h and Simulated Transportation at 30 °C for 15 h

4.3.3 Transpiration Rate and Vital Heat from Respiration in Different Covers

The transpiration rate and vital heat of okra under the six treatments were measured during simulated storage at 18 °C for 48 h and simulated transportation at 30 °C for 15 h. The major contribution of mass loss in pear and pomegranate was due to transpiration rather than respiration [32, 46]. In this study, differences among the six treatments were observed in transpiration rate compared to vital heat under both simulated storage and transportation conditions. This implied that thermal insulation materials influenced transpiration rate (mass loss) more than vital heat from respiration rate (Figure 4.10). During simulated storage, no cover and P-LLDPE provided the

highest transpiration rates (12.53 and 15.56 g h^{-1} m^{-2}, respectively), compared to the other four cover treatments. Under increased temperature during simulated transportation, transpiration rate of all six treatments increased gradually to more than double com-pared to okra under simulated storage. Highest transpiration rate was found in no cover as the control (35.11 g h^{-1} m^{-2}) followed by P-LLDPE (16.85 g h^{-1} m^{-2}), MTyvek (15.76 g h^{-1} m^{-2}), MFS (9.06 g h^{-1} m^{-2}) HRS+TNNW (9.05 g h^{-1} m^{-2}) and HRS+TKNW (8.53 g h^{-1} m^{-2}) (Figure 4.10A). This indicated that increase in temperature inside the four thermal insulation cover treatments had less effect on transpiration rate compared to no cover and P-LLDPE treatments. A study on P-LLDPE cover material by Rattanakaran et al. [47] revealed that transpiration rate of okra at 25 °C was greater than at 5 °C (5.16 and 1.93 g h^{-1} m^{-2}, respectively) after 48 h of testing. Lower transpiration rates in thermal insulation treatments related to their lower WVP, except for TNNW. Lowest transpiration rates of HRS and MFS materials related to the lowest WVP levels (Figure 4.10 and Table 4.2). The double layer of HRS+TNNW protected the transpiration rate of okra (Figure 4.10A).

During simulated storage, no significant difference in vital heat was observed among the six treatments. In this study, MTyvek (6850 J kg^{-1} h^{-1}) exhibited the lowest vital heat level compared with the other five treatments during simulated transportation at 30 °C for 15 h with no difference among P-LLDPE, HRS+TNNW and MFS covers (Figure 4.10B). Our results confirmed previous findings of Rattanakaran et al. [16]. The vital heat of okra inside thermal insulation cover (HRS+TNNW and MFS) was lower than that inside P-LLDPE at 30 °C for 1 h, while HRS+TNNW exhibited a lower vital heat than MFS and P-LLDPE at 30 °C for 15 h as simulated transportation. In this study, the box plot of MTyvek showed the lowest mean, median and maximum pulp temperature levels during simulated transportation compared with the other treatments, except for no cover (Figure 4.5). The thermal image of MTyvek exhibited a blue color, similar to the no cover treatment, whereas the other thermal insulation covers showed an orange color (Figure 4.7) due to higher heat transfer to the environment as well as improved air ventilation in MTyvek than in the other thermal insulation covers.



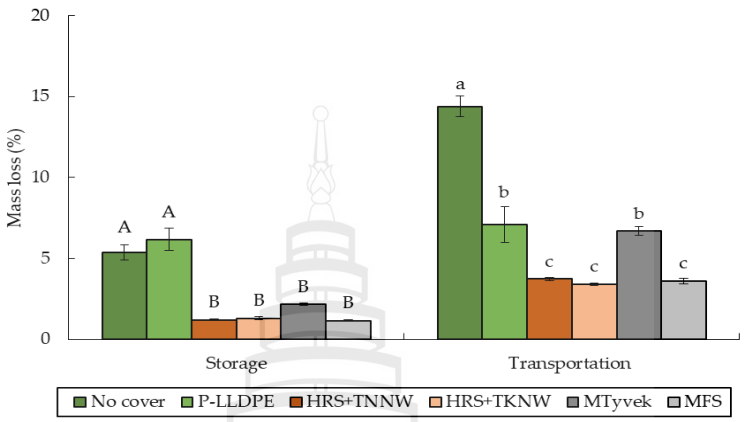
Note Different letters indicate significant differences at $p<0.05$. Values are mean ± S.E. from five replicates

Figure 4.10 Transpiration Rate (A) and Vital Heat (B) among the Six Treatments during Simulated Storage at 18 °C for 48 h and Simulated Transportation at 30 °C for 15 h

4.3.4 Mass Loss of Okra

After simulated storage, okra pods in no cover and P-LLDPE treatments showed significant mass loss of fresh weight at 5-6% compared to those of the other four thermal insulation material treatments (approximately 1%). Similarly, after simulated transportation, no cover showed the highest percentage of mass loss (14.4%) followed by P-LLDPE (7.1%), MTyvek (6.6%), HRS+TNNW (3.7%), HRS+TKNW (3.4%) and MFS (3.6%). Combined HRS with nonwovens and MFS treatments gave lower mass loss than MTyvek (2%), P-LLDPE (3.5%) and no cover (11%) (Figure 4.11). Similarly, HRS+TNNW and MFS had the lowest mass loss of okra (< 5%) compared to P-LLDPE (15%) throughout simulated storage and transportation [16]. High mass loss observed in no cover and P-LLDPE treatments corresponded to high transpiration rates (Figure 4.10A), high rates of air and pulp temperature changes (Table 4.3) and low RH levels (Figure 4.9). Scant research has addressed how thermal insulation covers can be applied to reduce mass loss in fresh fruits and vegetables. This finding supports previous reports on thermal insulation materials that reduced mass loss in amaranth when covered with an insulated pallet cover of Reflectix^{TM} composed of aluminum foil/0.8cm

polyethylene/bubble pack. They also found that insulated pallet cover (2%) reduced mass loss better than no cover (11%) during 6 h of display at a retail market [20].



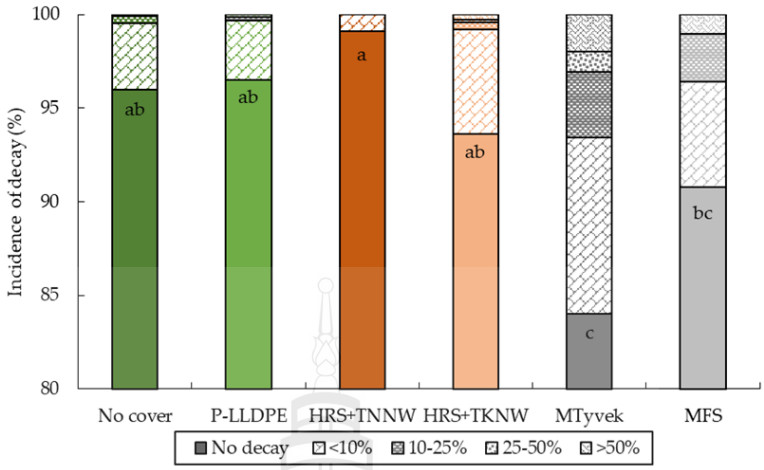
Note For Tukey's HSD post hoc test, different letters in each simulation test indicate significant differences at $p<0.05$. Values are mean ±S.E. from five replicates

Figure 4.11 Mass Loss (%) among the Six Treatments after Simulated Storage at 18 °C for 48 h and Simulated Transportation at 30 °C for 15 h

4.3.5 Incidence of Decay

MTyvek treatment exhibited the lowest percent of no decay (84.0%) compared with MFS (90.8%), HRS+TKNW (93.6%), no cover (95.9%), P-LLDPE (96.5%) and HRS+TNNW (99.1%) (Figure 4.12). The HRS+TNNW treatment exhibited the best thermal insulation performance to prevent postharvest loss of okra from decay (lowest decay incidence with 0.9%) and was found better than HRS+TKNW (higher decay incidence with 6.4%) (Figure 4.13). There are several possible explanations for this result. Firstly, thin nonwoven (TNNW) and perforated HRS combined with partial bonding, providing air space between the two layers. The TNNW material absorbed moisture from transpiration and respiration processes. Secondly, the moisture inside the cover passed through the nonwoven (inner layer) to the air space between the layers and provided an area for collecting moisture. From our observations, after the simulated transportation, HRS+TKNW, MTyvek and MFS exhibited moisture condensation on the inner side of the cover and this yielding a higher rate of decay, compared to

HRS+TNNW. Low WVP level of MTyvek and MFS (Table 4.2) reduced moisture vapor transfer to the outside, thus leading to high decay. Observation on decay of okra in this study was consistent with Rattanakaran et al. [16], which reported the lowest per-centage of okra decay (< 20%) in treatments of room cooling combined with HRS+TNNW and MFS, compared to that in P-LLDPE (50%). The results implied that room cooling for okra was important before covering, and significantly reduced okra decay. This result concurred with Emond and Germain [48] who reported that pallets covered with metalized bubble wrap had high condensation on the cases that led to rapid decay and increased mold growth in 'Kent' mango. From our findings, the application of thermal insulation covers was suggested for short periods of okra transportation under high temperature to reduce decay and heat accumulation. Gas treatment may reduce decay and control insects by active modified atmosphere packaging inside thermal insulation covers. In strawberry, flushing CO_2 gas (10-16%) within the pallet cover was applied to reduce decay during truck transportation. Tectrol pallets treated with a partial vacuum and flushing CO_2 exhibited significantly less decay (36%) compared to the noncovered control (41%) [49]. Phosphine fumigation was also applied in thermal insulation covers to control western flower thrips in chilled lettuce [40].



Note No decay shown by different letters in each treatment indicates significant differences at $p<0.05$ for Tukey's HSD post hoc test. Values are mean ± S.E. from five replicates

Figure 4.12 The Percentage of Decay Incidence in Six Treatments after Simulated Storage at 18 °C for 48 h and Simulated Transportation at 30 °C for 15 h

Figure 4.13 Okra from Six Treatments after Simulated Storage at 18 °C for 48 h and Simulated Transportation at 30 °C for 15 h

4.3.6 Pearson Correlation Analysis

In Table 4.4, material properties (thermal heat energy, R-value and WVP), temperature variables (rate of air and pulp temperature change at initial temperature (T_1) to 25 °C and 25 °C to 30 °C, accumulated time-temperature), okra quality (transpiration rate and vital heat during simulated storage and transportation, mass loss and decay incidence) were analyzed, using Pearson correlation, to present correlation coefficient value (*r*). Mass loss of okra showed positive correlation with thermal heat energy (Q_x) (*r* = 0.702) and transpiration rate (TR) during simulated storage (*r* = 0.898) and simulated transportation (*r* = 0.995), while mass loss of okra showed negative correlation with R-value (*r* = -0.729) and accumulated time-temperature (ATT) (*r* = -0.939). For the selection of thermal insulation materials, thermal heat energy (Q_x) (*r* = 0.702) and R-value (*r* = -0.729) properties were considered more than WVP to reduce mass loss in okra. Decay incidence of okra was related to WVP (*r* = -0.682), vital heat (VH) during transportation (*r* = -0.744) and rate of pulp temperature change during 25 °C to 30 °C (*r* = -0.823). The ATT throughout the simulated supply chain showed high correlation with both transpiration rate (TR) storage (*r* = -0.770) and TR transportation (*r* = -0.922) as well as mass loss (*r* = 0.939). Thus, the time-temperature variable affected transpiration as well as mass loss of okra throughout the supply chain. Results indicated that minimizing mass loss in okra could be achieved by focusing on thermal heat energy (Q_x) and R-value properties, which were identified as more significant factors than WVP. Minimizing decay incidence required attention on WVP, vital heat and rate of temperature change inside the covering.

Table 4.4 Pearson Correlation Analysis Evaluating by Material Properties, Transpiration Rate, Vital Heat, Air and Pulp Temperatures and Okra Quality

	Qx	WVP	R value	TR_ storage	TR_ transport	VH_ storage	VH_ transport	RoP T1to25	RoP T25to30	RoA T1to25	RoA T25to30	ATT	ML	Decay
Qx	1.000													
WVP	0.674**	1.000												
R_value	-0.925**	-0.791**	1.000											
TR_ storage	0.743**	0.723**	-0.874**	1.000										
TR_ transport	0.679**	0.549*	-0.720**	0.911**	1.000									
VH_ storage	-0.361	-0.407	0.408	-0.283	-0.175	1.000								
VH_ transport	0.205	0.406	-0.441	0.203	-0.089	-0.102	1.000							
RoP T1to25	0.659**	0.849**	-0.851**	0.819**	0.625*	-0.278	0.578*	1.000						
RoP T25to30	0.287	0.519*	-0.503	0.340	-0.046	-0.214	0.781**	0.651**	1.000					
RoA T1to25	0.743**	0.745**	-0.816**	0.692**	0.543*	-0.524*	0.343	0.647**	0.364	1.000				
RoA T25to30	0.514*	0.695**	-0.760**	0.712**	0.518*	-0.402	0.721**	0.854**	0.624*	0.635*	1.000			
ATT	-0.655**	-0.310	0.605*	-0.770**	-0.922**	0.104	0.284	-0.414	0.210	-0.416	-0.294	1.000		
ML	0.702**	0.537*	-0.729**	0.898**	0.995**	-0.164	-0.088	0.633*	-0.052	0.532*	0.506	-0.939**	1.000	
Decay	-0.271	-0.682**	0.449	-0.216	0.128	0.289	-0.744**	-0.622*	-0.823**	-0.488	-0.525*	-0.365	0.132	1.000

Note Rate of pulp temperature changes (RoP); rate of air temperature changes (RoA); water vapor permeability (WVP); transpiration rate (TR); thermal heat energy (Qx); vital heat (VH); accumulated time-temperature (ATT); mass loss (ML). **Correlation is significant at the 0.01 level (2-tailed). *Correlation is significant at the 0.05 level (2-tailed)

4.3.7 Hierarchical Clustering Analysis

To compare the efficiency between the two thermal insulation cover prototypes and commercial covers, the overall performance of all treatment covers was analyzed by Hierarchical clustering analysis (HCA). Three main parameters; material properties (thermal heat energy, R-value and WVP), temperature variables (rate of air and pulp temperature change at the initial temperature (T_1) to 25 °C and 25 °C to 30 °C and accumulated time-temperature) and okra quality (transpiration rate, vital heat during simulated storage and transportation, mass loss and decay) obtained from the five cover treatments, were analyzed as shown in Figure 4.14. The dendrogram identified various groups of packaging covers. The first division as in-groups consisted of HRS+TNNW and HRS+TKNW with MFS, while the second and third groups consisted of MTyvek and P-LLDPE, respectively. Both developing prototypes of thermal insulation covers (HRS+TNNW and HRS+TKNW) exhibited material properties that affected temperature fluctuation and mass loss, similar to those of the commercial MFS cover. Interestingly, these prototypes (HRS+TNNW and HRS+TKNW) exhibited greater reduction of decay (approximately 8.3%) compared to MFS, while reducing mass loss (quantitative loss) to 2% and decay (quality loss) to 15.1% compared with the commercial MTyvek cover. Dieckmann et al. [50] studied the efficiency of nonwoven fabric as a base material for temperature-controlled deliveries. They found that air-laid nonwoven feather fiber showed potential for temperature control compared with the commercially available expanded polystyrene (EPS) packaging panel. In terms of environmental aspects and packaging sustainability, combined HRS and selected nonwoven material should be developed as a thermal insulation prototype for cover application to reduce foam material (MFS), with lower postharvest loss (decay 1%) for distribution packaging.

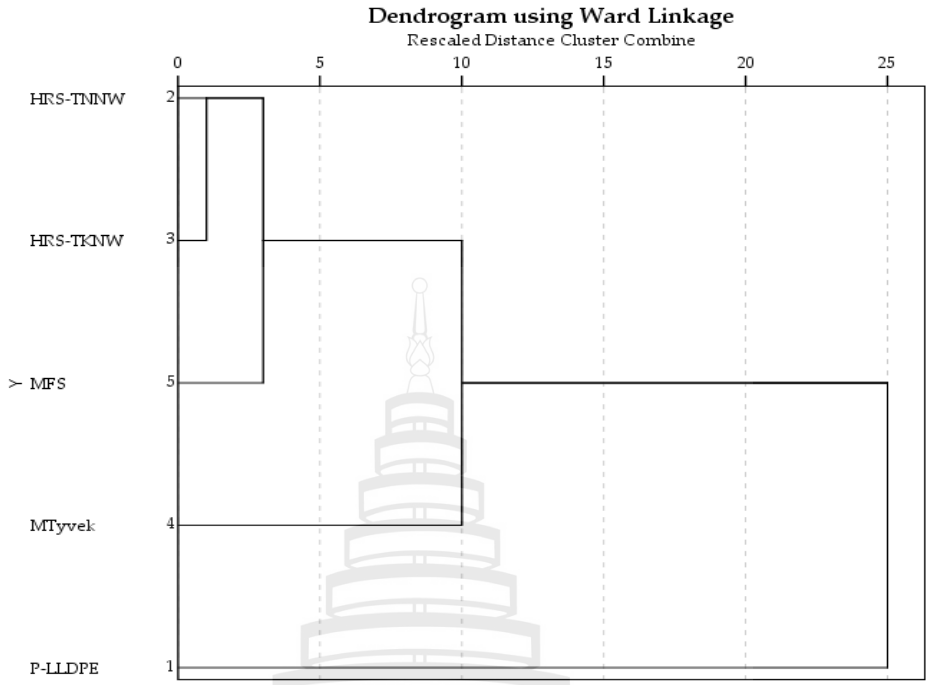


Figure 4.14 Hierarchical Cluster Analysis Based on Material Properties, Transpiration Rate, Vital Heat, Air and Pulp Temperatures and Okra Quality. Ward's Method for Dissimilarity was Utilized during Agglomerative Hierarchical Clustering

4.4 Conclusions

The performance of thermal insulation covers on preserving quality of okra was evaluated. With MTyvek and MFS covers, the high moisture retention resulted in more condensation and greater decay (16.0% and 9.2%), while P-LLDPE (3.5%) and HRS + TNNW (0.9%) had lower levels than no cover (4.0%). Mass loss was significantly reduced by applying the HRS + TNNW, HRS + TKNW and MFS covers. Two thermal insulation prototypes; HRS combined with either TNNW or TKNW, showed good potential to maintain low temperature, reduce transpiration, and mass loss of okra compared to the two commercial thermal insulation materials (MTyvek and MFS) and typical plastic materials (no cover and P-LLDPE). Form results, it was suggested that thermal insulation covering for fresh okra should have material properties with low

thermal heat energy (Q_x), high R-value and moderate WVP value to preserve cool temperature and delay okra senescence.

Author Contributions

J.R. conducted experiments, analyzed data, interpreted results, and assisted manuscript writing. R.S. co-investigated, interpreted results, and assisted data analysis. N.A. assisted data analysis. S.P. assisted material analysis. C.P. co-investigated, supported cover materials, interpreted results in material analysis, and assisted manuscript writing. H.K. provided comments and suggestions for the final draft of the manuscript. C.B. provided comments and suggestions for the final draft of the manuscript. S.C. was the principal investigator of the research, responsible for the overall research management, interpretation of results, and manuscript writing. All authors have read and agreed to the published version of the manuscript.

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Institutional Review Board Statement

Not applicable.

Informed Consent Statement

Not applicable.

Data Availability Statement

The data presented in this study are available on request corresponding author.

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Conflicts of Interest

The authors declare no conflict of interest.

References

[1] Siemonsma, J. S. (1982). West african okra—Morphological and cytogenetical indications for the existence of a natural amphidiploid of *Abelmoschus esculentus* (L.) Moench and A. manihot (L.) Medikus. *Euphytica, 31*(1), 241-252.

[2] Thai Customs. (2021). *Statistic report 2020*. Retrieved February 12, 2021, from http://www.customs.go.th/statistic_report.php?lang=en&tariff_code=07099990003

[3] Tsado, E. K. (2015). Quality of postharvest handling of marketable okra fruits sold in Minna, Niger State, Nigeria. *European Journal of Agriculture and Forestry Research*, *3*(5), 33-45.

[4] Perkins-Veazie, P. (2016). Commodity summaries: Okra. In K. C. Gross, C. Y. Wang & M. Saltveit (Eds.), *The Commercial storage of fruits, vegetables and florist and nursery stocks* (pp. 430–432). Washington: United States Department of Agriculture (USDA).

[5] Finger, F. L., Della-Justina, M. E., Casali, V. W. D., & Puiatti, M. (2008). Temperature and modified atmosphere affect the quality of okra. *Scientia Agricola, 65*, 360-364.

[6] Babarinde, G. O., & Fabunmi, O. A. (2009). Effects of packaging materials and storage temperature on quality of fresh okra (*Abelmoschus esculentus*) fruit. *Agricultura Tropica et Subtropica*, *42*, 151-156.

[7] Cheng, Z., Gong, X., Jing, W., Peng, Z., & Li, J. (2018). Quality Change of Postharvest Okra at Different Storage Temperatures. *Journal of Food Engineering and Technology*, *7*(1), 43-43. doi: 10.32732/jfet

[8] Huang, S., Li, T., Jiang, G., Xie, W., . . . Duan, X. (2012). 1-Methylcyclopropene reduces chilling injury of harvested okra (*Hibiscus esculentus* L.) pods. *Scientia Horticulturae, 141,* 42-46. doi: 10.1016/j.scienta.2012.04.016

[9] Greis, N. P. (2011). *Management the "Cool Chain" A Cold Chain is Only as Cool as Its Warmest Link*. Retrieved September 9, 2021, from https://www.asiacold chainshow.com/uploads/Managing%20the%20Cool%20Chain.pdf

[10] 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*(4), 647-667. doi: 10.1111/1541-4337.12269

[11] Sargent, S. A., Fox, A. J., Coelho, E. C. M., & Locascio, S. J. (1996). Comparison of cooling and packaging methods to extend the post-harvest life of okra. *In Proceeding- Florida State Horticultural Society, 109,* 285–290.

[12] Rai, D. R., & Balasubramanian, S. (2009). Qualitative and textural changes in fresh okra pods (*Hibiscus esculentus* L.) under modified atmosphere packaging in perforated film packages. *Food Science and Technology International, 15*(2), 131-138. doi: 10.1177/1082013208106206

[13] Liu, J., Yuan, Y., Wu, Q., Zhao, Y., . . . Yang, B. (2017). Analyses of quality and metabolites levels of okra during postharvest senescence by 1H-high resolution NMR. *Postharvest Biology and Technology, 132*, 171-178. doi: 10.1016/j.postharvbio.2017.07.002

[14] Food and Agriculture Organization. (2012). *Good practice in the design management and operation of a fresh produce packing-house*. Retrieved September 9, 2021, from https://www.fao.org/3/i2678e/i2678e00.pdf

[15] Dhall, R. K., Sharma, S. R., & Mahajan, B. V. C. (2014). Development of post-harvest protocol of okra for export marketing. *Journal of Food Science and Technology*, *51*(8), 1622-1625.

[16] Rattanakaran, J., Saengrayap, R., Prahsarn, C., Kitazawa, H., & Chaiwong, S. (2021). Application of Room Cooling and Thermal Insulation Materials to Maintain Quality of Okra during Storage and Transportation. *Horticulturae, 7*(7), 188. doi: 10.3390/horticulturae7070188

[17] Burgess, G. (1999). Practical thermal resistance and ice requirement calculations for insulating packages. *Packaging Technology and Science: An International Journal, 12*(2), 75-80.

[18] Singh, S. P., Burgess, G., & Singh, J. (2008). Performance comparison of thermal insulated packaging boxes, bags and refrigerants for single-parcel shipments. *Packaging Technology and Science: An International Journal, 21*(1), 25-35. doi: 10.1002/pts.773

[19] Wang, G., Zhao, J., Wang, G., Mark, L. H., . . . Zhao, G. (2017). Low-density and structure-tunable microcellular PMMA foams with improved thermal-insulation and compressive mechanical properties. *European Polymer Journal, 95*, 382-393. doi: 10.1016/j.eurpolymj.2017.08.025

[20] Wheeler, L., Kitinoja, L., & Barrett, D. M. (2015). Use of insulated covers over product crates to reduce losses in amaranth during shipping delays. *Agriculture, 5*(4), 1204-1223. doi: 10.3390/agriculture5041204

[21] Sharp, A. K., & Irving, A. R. (1981). *Insulating covers for pallets of food*. Scotland: AK, Sharp.

[22] Melis, R. B. (2016). *New techniques and methods for cold chain monitoring and tracking in perishable products*. Doctoral dissertation. Universidad Politécnica de Madrid, Madrid.

[23] Chaiwong, S., & Bishop, C. F. H. (2015). Use of an insulated bag from the supermarket to maintain ‘Elsanta’ strawberry temperature to households. *Acta Horticulturae, 1079*, 187–192. doi: 10.17660/ActaHortic.2015.1079

[24] Kitinoja, L. (2013). Use of cold chains for reducing food losses in developing countries. *Population*, *6*(1.23), 5-60.

[25] Harvey, B. V. (2006). *Mild chilling injury of banana (Cavendish cv. Williams) and its control in the field*. Doctoral dissertation. The University of Adelaide, Adelaide.

[26] American Society for Testing and Materials (ASTM). (2005). *Standard Test Methods for Water Vapor Transmission of Materials (ASTM E96)* (pp. 785-792). Pennsylvania: ASTM International.

[27] American Society for Testing and Materials (ASTM). (1996). *Standard Test Method for Air Permeability of Textile Fabrics; D737-96* (pp. 230-234). Pennsylvania: ASTM International.

[28] Saltviet, M. E. (2015). *Measuring Respiration*. Retrieved November 10, 2020, from http://ucce.ucdavis.edu/files /datastore/234-20.pdf

[29] Postharvest Research Laboratory. (2004). *Laboratory manual for horticulture postharvest technology* (pp. 24-27). Nakhon Pathom: Kasetsart University.

[30] Kader, A. A., & Saltveit, M. E. (2003). Respiration and gas exchange. In J. A. Bartz & J. K. Brecht (Eds.), *Postharvest Physiology and Pathology of Vegetables* (2nd ed., pp. 7–29). New York: Marcel Dekker Inc.

[31] Patel, B. B., Roy, F. S., Saiyad, M. J. S., & Joshi, D. C. (2016). Respiration behaviour and heat of respiration of mango (cv. Langdo) under different storage conditions. *International Journal of Agriculture, Environment and Biotechnology*, *9*(5), 855-859. doi: 10.5958/2230-732X.2016.00110

[32] Lufu, R., Ambaw, A., & Opara, U. L. (2019). The contribution of transpiration and respiration processes in the mass loss of pomegranate fruit (cv. Wonderful). *Postharvest Biology and Technology, 157*, 110982. doi: 10.1016/j.postharvbio.2019.110982

[33] Iweka, C., & Uguru, H. (2019). Environmental factors on the physical characteristics and physiological maturity of okra (*Abelmoschus esculentus*, cv. Kirikou) pods and seeds. *Direct Research Journal of Agriculture and Food Science (DRJAFS), 7*(5), 99-109.

[34] Ngure, J. W., Aguyoh, J. N., & Gaoquiong, L. (2009). Interactive effects of packaging and storage temperatures on the shelf-life of okra. *ARPN Journal of Agricultural and Biological Science, 4*(3), 44-49.

[35] Harding, K. G. (2018). *Heat Transfer Introduction*. Retrieved September 9, 2021, from https://www.researchgate.net/publication/323144799_Heat_transfer_introduction

[36] Mangaraj, S., Goswami, T. K., & Panda, D. K. (2015). Modeling of gas transmission properties of polymeric films used for MA packaging of fruits. *Journal of Food Science and Technology, 52*(9), 5456-5469.

[37] Manikantan, M. R., & Varadharaju, N. (2012). Preparation and properties of linear low-density polyethylene based nanocomposite films for food packaging. *Indian Journal of Engineering and Materials Sciences, 19*, 54-66.

[38] Dutta, A. (2015). *Redesigning the coffee laminate from aluminum foil based laminate to metalized polyethylene terephthalate laminate: A comparative study*. Doctoral dissertation. Asian Institute of Technology, Pathum Thani.

[39] *Dupont™, Tyvek® cargo Covers: The science behind the covers*. Retrieved November 10, 2020, from http://www.dupont.com/products-and-services/fabrics-fibersnonwovens/covers/articles/air-cargo-covers-science-behind.html

[40] Liu, Y. B. (2011). Low-temperature phosphine fumigation of chilled lettuce under insulated cover for postharvest control of western flower thrips, *Frankliniella occidentalis* (Pergande) (Thysanoptera: Thripidae). *Journal of Asia-Pacific Entomology, 14*(3), 323-325. doi: 10.1016/j.aspen.2011.02.003

[41] Gowen, A. A., Tiwari, B. K., Cullen, P. J., McDonnell, K., & O'Donnell, C. P. (2010). Applications of thermal imaging in food quality and safety assessment. *Trends in Food Science & Technology, 21*(4), 190-200. doi: 10.1016/j.tifs. 2009.12.002

[42] Bycroft, B. L., Brash, D. W., & Bollen, F. (1996). Using insulation and cooling to improve the asparagus cool chain. *Acta Horticulturae*, *415*, 323–332. doi: 10.17660/ActaHortic.1996.415.46

[43] Li, Y., Schrade, J. P., Su, H., & Specchio, J. J. (2014). Transportation of perishable and refrigerated foods in mylar foil bags and insulated containers: a time-temperature study. *Journal of Food Protection*, *77*(8), 1317-1324. doi: 10.4315/0362-028X.JFP-13-422

[44] *Dupont™, Tyvek® air cargo covers offer ideal protection for your perishable and temperature-sensitive shipments*. Retrieved June 11, 2021, from https://www.r-bag.hu/upload/files/DP-Tyvek-Air-cargo-cover-Brochure-K24389-2013.pdf

[45] Lim, B. S., Lim, C. I., & Gross, K. C. (2005). High relative humidity under Pallet Coverage Maintained 'Niitaka'Pear Fruit (*Pyrus pyrifolia Nakai*) Quality during Low Temperature Storage. *Korean Journal of Horticultural Science and Technology, 23*(2), 135-139.

[46] Xanthopoulos, G. T., Templalexis, C. G., Aleiferis, N. P., & Lentzou, D. I. (2017). The contribution of transpiration and respiration in water loss of perishable agricultural products: The case of pears. *Biosystems Engineering, 158*, 76-85. doi: 10.1016/j.biosystemseng.2017.03.011

[47] Rattanakaran, J., Saengrayap, R., Prahsarn, C., & Chaiwong, S. (2020). *Model development and validation for mass loss attributes of okra under dynamic conditions*. In Proceedings of the International Conference on Food and Applied Bioscience on 6-7 February 2020 (pp. 134–139), Chiang Mai: Chiang Mai University.

[48] Emond, P. J., & Germain, M. (2017). *Report: Study of thermal protection for mango pallets during mixed load shipment, National Mango Board*. Retrieved June 11, 2021, from https://www.mango.org/wpcontent/uploads/2018/03/Thermal_Protection_for_Mango_Pallets_Eng-1.pdf

[49] Macnish, A. J., Padda, M. S., Pupin, F., Tsouvaltzis, P. I., . . . Mitcham, E. J. (2012). Comparison of pallet cover systems to maintain strawberry fruit quality during transport. *HortTechnology, 22*(4), 493-501. doi: 10.21273/HORTTECH.22.4.493

[50] Dieckmann, E., Nagy, B., Yiakoumetti, K., Sheldrick, L., & Cheeseman, C. (2019). Thermal insulation packaging for cold-chain deliveries made from feathers. *Food Packaging and Shelf Life, 21*, 100360. doi: 10.1016/j.fpsl.2019

CHAPTER 5

CONCLUSIONS

In this study, the first experiment investigated the efficiency of room cooling and thermal insulation covers to reduce postharvest losses of okra under simulated storage and transportation. Room cooling at 0 °C for 2 h was observed as a pre-treatment for a heat removal before covering with thermal insulation materials. After simulated cool storage and high-temperature transportation conditions, the cooling with HRS+TNNW cover was more efficient in maintaining cool temperature with lower temperature level than other five treatments by 2 °C at the end of simulation tests. The cooling combined with HRS+TNNW provided the lowest postharvest loss (15%) compared to no cooling plus HRS+TNNW (26%), no cooling with MFS (52%), cooling plus P-LLDPE (59%), and TP (65%). In this study, it was demonstrated that room cooling is an essential pre-treatment in the postharvest handling of okra before covering to reduce heat accumulation under high temperature environment.

In the second experiment, okra samples were cooled by room cooling for 2 h before covering test. HRS combined with either TNNW or TKNW as thermal insulation prototypes exhibited reducing transpiration, mass loss and decay of okra as compared to the two commercial thermal insulation materials (MTyvek and MFS) and typical plastic materials (no cover and P-LLDPE). HRS+TNNW cover (5%) had the lowest postharvest loss of okra, followed by HRS+TKNW (10%), P-LLDPE (11%), MFS (13%), no cover (18%), and MTyvek (23%), respectively. A low thermal heat energy (Q_x), high R-value and moderate WVP value should be addressed for designing thermal insulation material for okra covering. Overall conclusion, the combined room cooling and HRS+TNNW performed the greatest cover to reduce postharvest losses of okra under simulated temperature condition for storage and transportation.

CHAPTER 6

SUGGESTION

In this study, the combined room cooling and HRS+TNNW cover exhibited greater performance for maintaining cool temperature and reducing postharvest loss of okra as compared to commercial covers (MTyvek and MFS) and P-LLDPE bag. This is the first published report to demonstrate that a room cooling is an important stage of okra handling before covering with thermal insulation materials. Therefore, no cooling treatment before covering should be reconsidered and avoided to apply for thermal insulation covering for protecting heat accumulation and lead to alleviate heat injury, senescence and decay. To delay an increase of temperature inside thermal insulation covers, gel packs or gel phase change materials (PCMs) should be applied in those covers to delay increasing tempter and may delay fresh produce deterioration. According to negative results of MFS under heat condition as simulated transportation, MFS cover exhibited high heat accumulation and decay. MFS should be avoided to cover under high temperature environment (>30 °C) to protect condensation inside cover and heat accumulation.

This work is a preliminary study to examine the efficacy of HRS+TNNW prototype, the prototype should be further designed to develop extra properties or functions such as thickness, binding and folding. In addition, this prototype as a thermal insulation cover may be tested in okra under an actual transportation and other perishable crops with moderate to high respiration level in both simulated and actual transportations. For other aspects of both transportation, okra pods are very sensitive in mechanical damages. Interestingly, thermal insulation cover will be applied and examined under vibration, impact and compression forces to observe reducing browning incidence from mechanical damages.

APPENDIX

APPENDIX

RESEARCH PAPER

Proceedings

International Conference on Food and Applied Bioscience (FAB 2020)

February 6-7, 2020

at

Chiangmai Grandview Hotel & Convention Center

Organizer

Faculty of Agro-Industry, Chiang Mai University

Co-Host

Proceedings of International Conference on Food and Applied Bioscience (FAB2020)

Editor-in-chief Assistant Professor Dr. Sujinda Sriwattana
Prepared by Faculty of Agro-Industry, Chiang Mai University
May 2020 (available in PDF file only)

The International Conference on Food and Applied Bioscience 2020:
Insights for Research and Industry 4.0

Model Development and Validation for Mass Loss Attributes of Okra under Dynamic Conditions

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Abstract: Okra (*Abelmoschus esculentus* L.) is a highly perishable fruit which has high moisture content and respiratory activities. Water loss or transpiration is a critical problem and important physiological process that affects the main quality characteristics of fresh okra. Most of the publications on modelling this phenomenon consider constant temperature and relative humidity (RH) during the storage. The aim of this research study was to develop a methodology of a mass loss model for okra and validate its prediction in dynamic environment conditions during simulated transport condition. For developing transpiration rate model, okra pods (250 grams) were packed in perforated linear low-density polyethylene (LLDPE) bag and stored under 3 conditions which were 5°C±99%RH, 15°C±95%RH and 25°C±66%RH. The weight of each sample was measured every 2 days for 8 days (48, 96, 144, and 192 h). For validation of model by transport simulation condition, the simulation test by using two conditions included 18°C for 48 h for storage and 30°C for the simulated transport about 15 h. The results showed that normalized weight of okra from three different storage conditions decreased constantly from 1.00 to the range of 0.88 to 0.96 after storage for 192 h. Also, transpiration rate of okra ranged from 0.48 g h^{-1} kg^{-1} (5°C) to 1.33 g h^{-1} kg^{-1} (25°C) after storage for 192 h. For modelling in constant condition, the mass of observed value was a high correlation with that of predicted value as determination coefficient (R^2=0.995), mass transfer coefficient (k_i) 6.306 g h^{-1} kg^{-1} and coefficient constant (a) 2.407°C^{-1}. Those k_i and a values were validated by dynamic environment conditions. The result showed the high correlation between observed value and predicted value of okra weight (R^2=0.966). Therefore, the model approach is useful to predict mass loss of okra under dynamic condition with variable temperature, relative humidity, and time.

Keywords: Moisture loss; Predictive modelling; Storage temperature; Transpiration rate

1. Introduction

Okra (*Abelmoschus esculentus* L.) is an annual vegetable crop and belongs to the family Malvaceae. Okra is a highly perishable fruit which has high moisture content and respiratory activities. The causes of postharvest losses in okra are mechanical damages, pathological defects, yellowing symptoms and physiological defects (Flores *et al.*, 2018) as well as the wilting and shriveling symptoms from transpiration which showed ridge blackening and black discoloration along the ribs. (Kader, 1983). The optimum storage condition is the range temperature of 7 to 10°C and relative humidity (%RH) around 95 to100% which can be stored satisfactorily for 7 to 10 days. (Hardenburg *et al.*, 1986; Ngure, 2009). The fresh okra pods have an extremely short shelf life due to high water loss rates.(Tamura *et al.*, 1984) The storage of okra at 25°C increased weight loss (14%) after storage for 5 days due to wilting, yellowing, and decay (Finger *et al.*, 2008). Transpiration

rate was found to be better expressed in quantity of water loss per unit time per unit fresh weight. Leonardi *et al.,* 1999 [7]

Mathematical modelling has the ultimate goal of predicting future behavior of the products in any circumstances (Tijskens and Schouten, 2009) . In some of the reported works, the transpiration process was related to changes in texture attributes (Smedt *et al.,* 2002) and visible wrinkling of the fruit skin (Hertog, 2002). However, even though the transpiration from fruit can be well described by the approach of steady state solution of Fick's first law, most of the publications on modelling this phenomenon consider constant temperature and RH during the storage time. (Hertog *et al,.* 2004; Maguire, *et al.,* 1999, Mahajan *et al.,* 2008) Recently, the modelling study in table grape for water loss estimation was reported by Pereira *et al.*(2018) The result showed that the model under dynamic storage conditions could describe the water loss of table grape effectively and the validation tests confirmed its predictive capability.

However, very little was known about okra transpiration rate and weight loss behavior under variable conditions of temperature, relative humidity and time. Therefore, this study aimed to propose a methodology to develop a weight loss model for okra and validate its predictions in dynamic environment conditions during simulated transport condition.

2. Materials and Methods

2.1 Material

Okra (*Abelmoschus esculentus* L.) was harvested around 45 days after planting or 6 days after flowering from the okra plantation in Dok Kham Tai district, Phayao province. The okra pods were transported from farm to the postharvest laboratory at Mae Fah Luang University within 2 h. After the arrival at the laboratory, okra pods were graded in uniformity size with the pod length of 7 to 11 cm (the specific size for okra processing) and had minimum requirement in fresh, green in color, free of distinct signs of bruising, smooth and clean in peduncle cut surface. The okra pods around 250 grams were packed in perforated linear low-density polyethylene (LLDPE) plastic bag (six holes) and triplicates for each storage condition. All the samples were weighted using a digital weight scale (PB4001-S, Mettler Toledo, Switzerland) to get the mass of okra.

2.2 Experimental procedure

The experimental were divided into 3 temperature conditions which were 5°C at 99%RH, 15°C at 95%RH and 25°C at 66%RH. Air temperature were measured inside the three storage conditions by using Tinytag Talk 2 (TK-4014-PK) and relative humidity by using Tinytag Ultra 2 (TGU-4500).

2.3 Development of the transpiration rate model

In terms of the weight loss profile, the mass of each sample was measured every two days for eight days after the storage conditions for calculating normalized weight (M/M_i), where M and M_i are the weight and the initial weight (g). According to the Fick's law of diffusion, this is proportional to the difference between humidity of fruit internal atmosphere and humidity of the surrounding air (Ben-Yehoshua, 1987). The transpiration rate of okra was calculated the amount of water loss from the plant per unit weight per unit time from Equation 1 which developed for calculation the transpiration rate of mushrooms and table grape. (Pereira *et al.,* 2018; Smedt *et al.,* 2002)

$$TR = k_t \times (a_{wi} \cdot a_w) \times (1\text{-}\exp(-aT)) \quad (1)$$

Where TR is the transpiration rate (g h^{-1} kg^{-1}), expressed as a function of temperature and RH; k_i is the mass transfer coefficient (g h^{-1} kg^{-1}); a_{wi} is the determined average water activity of the okra (0.995); a_w is the water activity of the container (RH/100); a is a coefficient constant ($°C^{-1}$); T is the temperature (°C).

Sousa-Gallagher *et al.* (2013). have combined Equation 1 with a technique reported by Leonardi *et al.* (1999) Equation 2 for evaluating transpiration rate related to weight loss is resulted in Equation 3.

$$TR = M_i - M / t\ (M_i/1000) \quad (2)$$

$$M = M_i - K_i \times (a_{wi} - a_w)\ (1 - \exp(-aT))\ (M_i / 1000)\ t \quad (3)$$

Where M and M_i are the weight and the initial weight (g), respectively; t is the time (h).

Okra transpiration data obtained for all the combinations of temperature and %RH was used to estimate the values of constants k_i and a. Equation 2 was fitted by non-linear regression analysis using a Statistica software to estimate the model parameters.

Dynamic conditions model

Equation 4 was proposed to predict the weight of okra based on the fact with the initial weight is decreased by the sum of weight loss. In those time intervals, measured temperature (T_j) and container water activity (a_{wi}) was considered constant. Moreover, the parameter k_i was considered constant throughout the time intervals.

$$M = M_i - \Sigma k_i \times (a_{wi} - a_w) \times (1 - \exp(-aT_j)) \times (M_i / 1000)\ t_j \quad (4)$$

Validation of model by transport simulation condition trials

The okra around 1,500 gwere packed in a plastic basket with covered by perforated LLDPE plastic bag (6 holes). The okra pods were cooled under 0°C by a room cooling method for 2 h. For the simulation test, the sample was transferred to 18°C for 48 h for the simulated storage and transferred to 30°C for 15 h for the simulated transport. During the trial, the okra pods were weighted in three times including, before cooling, after 18°C for 48 h, and after 30°C for 15 h. The transpiration rate was calculated by the Equation 2. Each point of the experimental data curve corresponds to the average of four samples.

3. Results and discussion

3.1 Weight loss changes and transpiration rate of okra

As shown in Figure 1A, okra weight decreased constantly during storage at all storage temperatures (5°C, 15°C and 25°C). At the low storage temperature of 5°C, okra maintained the weight loss slower than those of higher temperatures. It shows that the low temperature storage can effectively reduce the loss of water after harvest. Finger *et al.*[6] found that the lower temperature at 5°C for 5 days reduced weight loss of okra (10%) when compared with the storage at 10°C (16%) and 25°C (27%). Similarly, the transpiration rate increased with an increase in temperature. Transpiration rate was calculated by fitting Equation 1 to experimental data as shown in Section 2.3. The transpiration rate ranged from 0.48 g h^{-1} kg^{-1} for the low temperature (5°C) to 1.33 g h^{-1} kg^{-1} for the high temperature (25°C) after storage for 192 h (Figure 1B). The transpiration rates of okra showed the same trend as reported in table grapes (Pereira, 2018) and pomegranate (Aindongo, 2004), that the increasing of storage temperature influenced the increasing of transpiration rate.

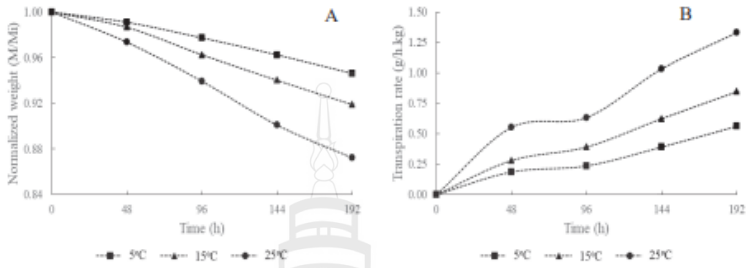

Figure 1 Changes in weight of okra (*M*) over time (h) (A) and transpiration rate (*TR*; g h^{-1} kg^{-1}) of okra during storage at three storage temperatures (B). Each point of the curve corresponds to the average of three samples. Standard errors (SE) are shown in error bars.

3.2 Development of the transpiration model

The constant coefficients (k_i and a) from the mathematic model (Equation 3) were estimated by using experimental data which obtained at all combination of constant temperature and relative humidity reported in section 2.2. The Statistica software with non-linear regression were used to estimate constant coefficients including mass transfer coefficient (k_i) 6.306 g h^{-1} kg^{-1} and coefficient constant (a) 2.407 $°C^{-1}$ of okra. The estimated parameter and standard errors (SE) by the regression are shown in Table 1. These value varied in table grape[14] and pomegranate[18] such as mass transfer coefficient (k_i) 0.474 g h^{-1}. kg^{-1} and 84.10 g h^{-1}. kg^{-1} as well as coefficient constant (a) 0.213$°C^{-1}$ and 0.05$°C^{-1}$, respectively. Figure 2 shows the relationships between the observed and predicted values of weight loss of okra by constant and dynamic conditions. Figure 2A shows the good agreement between observed and predicted mass of okra during constant condition with the high R^2 value of 0.995. In addition, the dynamic condition also showed the good agreement with R^2 value of 0.966 (Figure 2B). The present findings seemed to be consistent with the previous research in table grape (Pereira, 2018) and pomegranate (Aindongo, 2004) which were found that the transpiration rate model described the mass loss process sufficiently. In this study the developed modelling showed the capability for predicting the changes of okra weight over temperature and storage time in both constant and dynamic conditions.

Table 1 Estimated parameters of the mathematical model (Equation 3), where *ki* is the mass transfer coefficient (g h^{-1} kg^{-1}) and a is the overall effect of temperature coefficient ($°C^{-1}$), standard error (SE) of the estimation and determination coefficient (R^2).

k_i (SE)	a (SE)	R^2
6.306 (2.448)	2.407 (0.000)	0.995

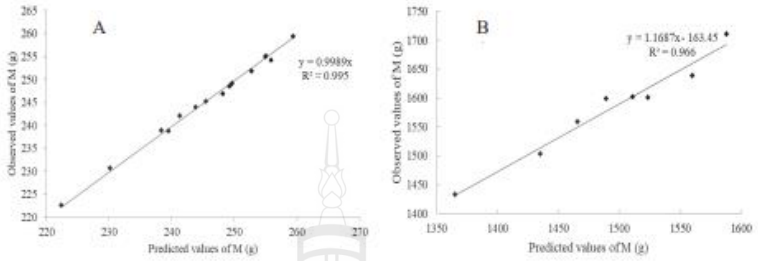

Figure 2 Relationship between observed and predicted weight of okra for all the experimental data obtained by constant condition (A) and dynamic condition (simulated storage and transport conditions) (B).

3.3 Validation experiments

The estimated parameters (Table 1) were used to predict the changes of okra weight. Figure 4 shows the good agreement between experimental and predicted values which was validated by evaluating the model predictions for the weight loss of okra by transport simulation condition trials. The goodness of fit for each validation test was determined by calculation of R^2 value (0.966) shows in Figure 2B. However, the temperature fluctuation profiles, as shown by Figure 4, might lower model prediction accuracy. In this study, the developed model was sufficient and confirming its predictive ability. In accordance with the present results, the modelling for transpiration rate of table grape approach presented the goodness of fit for dynamic condition as shown by R^2 value (0.995).[14]

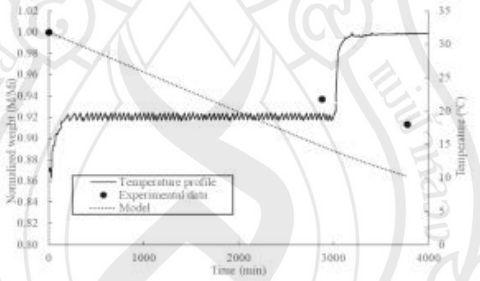

Figure 4 Relationship between the model predictions (dotted line) and the experimental data (symbols) for changes in mass of okra during dynamic condition.

4. Conclusion

The transpiration rate of okra ranged from 0.48 g h^{-1} kg^{-1} (5°C) to 1.33 g h^{-1} kg^{-1} (25°C) after storage for 192 h. The basis of Fick's law of diffusion considering the effect of temperature and relative humidity was developed as mathematic model and yielded adequate description of mass loss of okra during storage. Model development showed the high correlation between observed and predicted values of okra weight which predicted the weight

changes of okra over temperature and storage time in both constants (R^2=0.995) and dynamic condition (R^2=0.966). The validation experiment by dynamic condition showed the goodness of fit for validation test. The model approach was useful to predict mass loss of okra under dynamic condition with variable temperature, relative humidity, and time.

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References

1. Aindongo, W. V., Caleb, O. J., Mahajan, P. V., Manley, M., Opara, U. L. 2004. South African Journal of Plant and Soil. 31(1): 7-11.
2. Ben-Yehoshua, S. 1987. Transpiration, sater stress, and gas exchange; Weichmann J. Ed. Marcel Dekker Inc: New York. 113-170.
3. Finger, F. L., Della-Justina, M. E.; Casali, V. W. D. and Puiatti, M. 2008. Scientia Agricola. 65(4): 360-364.
4. Flores, E., Dela Cruz, R. and Antolin, M.C. 2018. Asian Journal of Postharvest and Mechanization. 46: 116-133.
5. Hardenburg, R. E., Watada, A. E. and Wang, C. Y. 1986. Commercial storage of fruits, vegetables, flowers and nursery stock. USDA Handbook. No. 66.
6. Hertog, M. L. A. T. M. 2002. Postharvest Biology and Technology. 26(3): 253-263.
7. Hertog, M. L. A. T. M., Ben-Arie, R., Róth, E. and Nicolaï, B. M. 2004. Postharvest Biology and Technology. 33(1): 79-91.
8. Kader, A.A. 1983. Postharvest quality maintenance of fruits and vegetables in developing countries; Lieberman M. Ed. Plenum Publ. Corp: New York. 455-570.
9. Leonardi, C., Baille, A., and Guichard, S. 1999. The Journal of Horticultural Science & Biotechnology. 74(6): 748-756.
10. Maguire, K. M., Banks, N. H., and Lang, A. Postharvest Biology and Technology 1999, 17(1): 11-17.
11. Mahajan, P. V. Oliveira, F. A. R. 2008. Macedo, I. Journal of Food Engineering. 84(2): 281-288.
12. Ngure, J. W., Aguyoh, J. N. and Gaoquiong, L. 2009. ARPN Journal of. Agricultural and Biological Science. 4(3): 43-52.
13. Pereira, E., SPAGNOL, W. A., and SILVEIRA JUNIOR. V. 2018. Food Science and Technology. 38(3): 473-479.
14. Smedt, V., Barreiro, P., Verlinden, B., Veraverbeke, E., Baerdemaeker, J. and Nicolaï, B. 2002. Postharvest Biology and Technology. 25(3): 273-291.
15. Sousa-Gallagher, M. J., Mahajan, P. V., Mezdad, T. 2013. Journal of Food Engineering 119(2): 370-376.
16. Tamura, J. and Minamide, T. 1984. Bulletin of the University of Osaka Prefecture. 36: 87-97.
17. Tijskens, L. M. M., Florkowski, W. J., Shewfelt, R. L.; Brueckner, B.; Prussia, S. E.Schouten, R. E. 2009. Modeling quality attributes and quality related product properties; Eds. Elsevier: Netherland. 411-448.

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Article

Application of Room Cooling and Thermal Insulation Materials to Maintain Quality of Okra during Storage and Transportation

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Abstract: A combination of room cooling and the use of thermal insulation materials to maintain okra quality under simulated storage and transportation was evaluated. Okra pods were packed in plastic baskets and either cooled at 18 °C or not cooled in a room for 2 h. After either room cooling or no cooling, the okra pods were covered with three different materials: (1) perforated linear low-density polyethylene (P-LLDPE), (2) two layers of heat-reflective sheet with thin nonwoven (HRS+TNNW), and (3) metalized foam sheet (MFS). Typical handling (TP) without cooling and covering with P-LLDPE was used as the control. The six treatments were conducted during simulated storage (18 °C for 48 h) and transportation (30 °C for 15 h). Results showed that MFS gave the best insulation properties (Q_s and R-values), followed by HRS and TNNW. After room cooling, both HRS+TNNW and MFS materials delayed the time for pulp temperature to reach 18 °C (10 h), compared to P-LLDPE (2 h). TP presented the highest mass loss (17.8%) throughout simulated conditions, followed by cooling plus P-LLDPE (15.2%) and either of the thermal insulation materials with or without room cooling (3.6% to 5.2%), respectively. TP, cooling plus P-LLDPE, and no cooling plus MFS (44% to 56%) showed the highest percentage of decay, while cooling combined with both HRS+TNNW and MFS gave the lowest decay incidence (11–21%). Findings demonstrated that room cooling combined with HRS+TNNW had the highest efficiency for preserving cool temperature and reducing decay, compared to TP and room cooling plus MFS.

Keywords: decay; covering; nonwoven; mass loss; metalized foam sheet

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1. Introduction

Okra (*Abelmoschus esculentus* L.) is an economic vegetable crop widely grown in tropical and sub-tropical global regions. Okra pods are harvested when immature and eaten as vegetables [1]. Okra is an export vegetable crop of Thailand, with the Japanese market accounting for 83.3% of the total exported okra volume. The main growing areas are the central and northern areas of Thailand [2]. A decline in the quality of okra is attributable to various issues, including techniques for determining okra fruit quality, poor harvesting methods, okra harvester training levels, lack of good vehicles, terrible roads, and insufficient pre-cooling facilities [3]. High respiration rate and rapid deterioration causes heat build-up and leads to pod blackening as well as a rapid increase in okra water loss after harvesting [4,5].

Temperature and relative humidity are the most important factors affecting the shelf life of okra [6]. The optimal storage temperature of okra ranged from 7 to 10 °C, and the pods can be stored satisfactorily for 7–10 days [7]. Fresh okra pods exhibited extremely

short shelf life due to high water loss or transpiration rates. Storage of okra at 25 °C resulted in a higher mass loss (14%) compared to a lower temperature of 4 °C after 5 days due to wilting, yellowing, and decay [8]. Storage at low temperatures led to a reduction of respiration rate, transpiration, and ethylene production [9]. At high temperatures, okra is highly susceptible to water loss, color fading, and decay, becoming squashy with a loss of commercial value and not easy to consume when fresh [10].

Heat generation, specifically known as 'Vital heat' in fresh produce, is produced as a by-product, primarily through the respiration process. Okra is classified at a very high respiration level, with a respiration rate of 40–60 mg CO_2 kg^{-1} h^{-1} and vital heat ranging from 427 to 640 J kg^{-1} h^{-1} at 5 °C [9]. Consequently, a cooling process should be taken into consideration when the storage room is designed as well as during transportation [11]. Cooling as quickly as possible after harvesting is critical to remove heat from the fresh produce and is a very important requirement for maintaining optimal product quality, especially for merchandise with naturally high respiration rates [12]. Forced-air cooling has been used for the export of okra received directly from the field [13]. In India, room cooling at 15 °C before storage at 8 °C is used for the export of okra [14]. The procedure of no cooling resulted in decreased fruit quality and increased fruit decay. Post-harvest loss of commercial fruits and vegetables increased by 25–30% when no cooling was employed through the whole storing and transporting chain, while it was only 5–10% when a cooling step at 8 °C was practiced [15]. Wang et al. [16] showed that room cooling at 2 °C reduced changes in the physiological quality of button mushroom (*Agaricus bisporus*). However, scant research has reported on cooling conditions and the efficiency of cooling processes to reduce heat generation in okra to extend storage or shelf life.

Thermal insulation materials are defined as materials or combinations of materials that retard the flow of heat to prevent or minimize temperature changes in the system or space [17]. Thermal insulation materials are normally used as pallet covering, combined with other materials, to protect fresh produce during transportation [18]. Thermal insulation material testing evaluates whether a packaging design succeeds in maintaining a temperature-sensitive product within its appropriate temperature range when exposed to ambient conditions [19]. The main thermal insulation properties are measured as thermal heat transfer and R-value. Heat transfer is the mechanism of energy movement due to temperature differences between two sources [20]. A low rate of heat transfer implies better insulation of the materials via reduction of conductive heat loss [21]. The resistance to heat flow through an insulation material, known as the R-value, is determined by ice-melt processing [22]. A higher R-value presents a better performance of thermal insulation materials [19].

Pallet cover is an alternative method used as packaging technology to reduce waste from food spoilage by minimizing temperature and humidity change during the transportation of fresh produce [18,23,24]. Research on packaging for vegetables revealed that covering the pallet side and bottom with insulated pallet cover (Reflectix™) resulted in a reduction of mass loss and wilting in amaranth and preserved a desirable dark green color. Use of pallet cover for amaranth gave a high score in overall quality, with improvement on no cover [18]. Liu [25] reported the use of an insulated cover to keep pre-chilled lettuce at low temperatures. The insulated cover was also suitable for low-temperature phosphine fumigation to control western flower thrips on harvested lettuce. Chaiwong and Bishop [23] reported on lightweight insulation bags. Results showed that insulated bags provided cool temperature management and reduced the cool chain breakdown of strawberries from the supermarket to domestic refrigerators. The insulated pallet covers also gave better temperature preservation compared to no cover, and temperature changes occurred more slowly in chard, cucumber, and carrot [18,23,24]. However, very few studies exist about the use of thermal insulation cover to prevent post-harvest losses of okra under different temperature conditions.

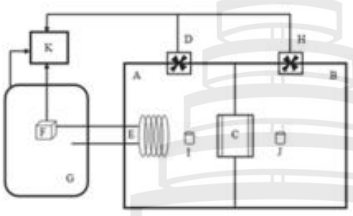
The main post-harvest problems of okra during domestic transportation are temperature and relative humidity fluctuation. These lead to physiological damages such as

wilting and fruit rot before the freeze-drying process. Cooling treatment could delay the deterioration of okra quality, whereas thermal insulation covering could improve controlling temperature and humidity fluctuations under typical truck transportation. In this study, the efficiency of room cooling and thermal insulation materials in controlling cool temperature and okra quality under simulated storage and transportation were evaluated.

2. Materials and Methods

2.1. Materials Properties

Thermal heat energy was determined according to the procedure of Harvey [21], using an expanded polystyrene box with dimensions (75 × 38 × 38.5 cm^3) with two sections (Figure 1). The material sample was taped on a hole (C) 10 cm × 10 cm to allow heat from the heated copper coil (E) at temperature 45 °C in section 1 (A) to pass through the material sample and enter section 2 (B). Temperature data loggers (Tinytag Talk 2: TK-4014-PK, Gemini Data Loggers, West Sussex, UK) were used to monitor the temperature change between the two sections (section 1 (I) and section 2 (J)) of the box for 3 h until a constant temperature was recorded. The rate of transfer of thermal heat energy (Q_x) in J s^{-1} was calculated.



A An expanded polystyrene box (section 1)
B An expanded polystyrene box (section 2)
C Square hole for material cover attachment (10 × 10 cm^2)
D Rotating fan (section 1)
E Heating coil
F Rotating pump
G Water bath at 45 °C
H Rotating fan (section 2)
I Data logger (section 1)
J Data logger (section 2)
K Power source

Figure 1. Schematic diagram for heat transfer test through material covers at the laboratory.

The water vapor permeability (WVP) through different materials was determined using the desiccant in cup method. Following ASTM E96 [26], the specimen or cover material was sealed on the open mouth of a test dish containing a desiccant, and the test dish was placed in a constant climate chamber (KBF-115, Binder, Tuttlingen, Germany) at 25 °C and 50% relative humidity (RH). Water vapor permeability was then calculated as rate of water vapor transmission in g h^{-1} m^{-2}.

Air permeability was determined using an air permeability tester (FX 3300 LabAir IV, Textest Instruments, Schwerzenbach, Switzerland) according to ASTM D737-04 [27]. Thermal insulation materials were cut into square pieces of 20 × 20 cm and measured for air permeability (l m^{-2} s^{-1}). The R-value was determined as resistance to heat flow through the thermal insulation material using the ice-melt test, following Singh et al. [19]. In this method, 2000 g of ice were placed in a non-metallic bucket, which was then positioned in the center of a basket inside thermal insulation bags and wrapped tightly with tape. The package was stored on a shelf at ambient temperature (25 °C) for 12 h. At the end of the test, the thermally insulated containers were opened, and water was collected from the buckets. The weight of water was recorded to calculate the melt rate (m^2 °C W^{-1}). Five samples (replications) in each material were tested.

2.2. Plant Materials

'Lady Finger' okra pods from Green Global Seeds Company Limited, Thailand, were planted with the spacing between plant and row of 50 and 100 cm, respectively, with sprinkler irrigation. The okra pods were harvested 45 days after planting, or 6 days after flowering from an okra plantation (20°13′27.2″ N 99°50′05.2″ E), in Mae Chan district, Chiang Rai Province. The pods were transported from the farm to the Postharvest Laboratory at Mae Fah Luang University within 30 min. After arrival at the laboratory, the okra pods

were graded to uniform size of pod length 7–11 cm (the specific size for okra processing), with minimum requirements being green in color, free of distinct signs of bruising and disease, and a clean-cut peduncle.

2.3. Experimental Treatments and Heat from Respiration Rate (RR)

The research study was divided into two experiments.

2.3.1. Handling Procedures

Six treatments were studied. The control, as typical handling (TP) of the Phayao community enterprise (without room cooling and covered with perforated linear low-density polyethylene (P-LLDPE)) was compared with developing handling (DH), comprising room cooling, covered by two thermal insulation materials (heat-reflective sheet (HRS) + thin nonwoven (TNNW)), which were polypropylene (PP)-based spunbond nonwoven, and metalized foam sheet (MFS)), as shown in Table 1. It is noted that the HRS material was evenly perforated and distributed with a pin of diameter 0.55 mm for a total perforation area of 0.09 cm^2.

Table 1. Six treatments (with or without room cooling) using different material covers.

Treatment	Description
TP (Control)	No room cooling with P-LLDPE covering
DH1	Room cooling with P-LLDPE covering
DH2	No room cooling with HRS+TNNW covering
DH3	No room cooling with MFS covering
DH4	Room cooling with HRS+TNNW covering
DH5	Room cooling with MFS covering

For each treatment, 1500 g of okra pods were packed in a plastic basket (five replications). Initial temperature at the core of the okra pods was approximately 30 °C. Room cooling treatments (DH1, DH4 and DH5) were performed by setting the cooling medium at 0 °C for 2 h, compared with a cool room at 18 °C (no room cooling) (TP, DH2, and DH3) for 2 h as the 7/8 cooling time. Pulp temperature of the okra was monitored by a multichannel data logger (Hioki, LR8431, Nagano, Japan) connected with a type-K thermocouple for 10 channels. Five baskets each room cooling at 0 °C or at 18 °C were allocated for temperature monitor. After room cooling, the okra pods were covered with different thermal insulation materials, except for TP and DH1. Storage and transportation conditions of okra to simulate commercial practice before processing comprised storage at 18 °C for 48 h and transfer at 30 °C for 15 h.

2.3.2. Determination of Respiration Rate

Respiration rate of okra was determined under three storage conditions (10, 20, 30 °C) for 2 and 3 days. Okra pods (150 g) were packed in a plastic food container (8400 mL) (Figure 2). Respiration rate testing was conducted in a closed system for 2 h. A gas sample of 5000 µL was drawn from each container at daily intervals for gas chromatography (GC) analysis. A gas chromatograph (7890A, Agilent Technologies, California, USA) equipped with a thermal conductivity detector (TCD) and HayeSep Q column (80/100 mesh, 3.05-m long) was used to analyze the gas samples. Nitrogen was used as the carrier gas at a flow rate of 52.2 mL min^{-1} with split mode. Injector, oven, and detector temperature conditions were 150, 60, and 275 °C, respectively. The respiration rate (R_{CO2}) was determined on days 2 and 3 for the three storage conditions and calculated by the following Formula (1) [11];

$$R_{CO2}\ (mg\ CO_2\ kg^{-1}\ h^{-1}) = \frac{(CO_2\ (\%) \times \text{volume of container (mL)})}{100 \times (\text{fruit weight (kg)}) \times (\text{closing time (h)})} \quad (1)$$

Figure 2. Okra pods packed in a plastic food container for respiration rate measurement by a closed system.

The respiration rate (R_{CO2}) of okra pods in each closed system storage condition was calculated as the temperature coefficient (Q_{10}) value by Formula (2):

$$Q_{10} = (R_2R_1)^{10/(T_2-T_1)} \quad (2)$$

where R_2 and R_1 are the respiration rate at temperature T_2 and T_1, respectively [28].

The Q_{10} values on day 2 (48 h) and day 3 (72 h) were used to estimate the respiration rate of okra pods (R_C) in different air temperature levels using a temperature data logger (Tinytag Talk 2: TK-4014-PK, Gemini Data Loggers, West Sussex, UK). This depended on the thermal insulation cover treatments under simulated storage (18 °C for 48 h) and transportation (30 °C for 15 h), respectively. The air temperature for estimation of okra respiration rate (R_C) in each cover treatment was determined from the final air temperature level before simulated storage (R_{C1}) and transportation conditions (R_{C2}). Respiration rates of okra pods in each cover material were converted into vital heat by Formula (3) [29]:

$$\text{Vital heat (J kg}^{-1}\text{ h}^{-1}) = R_C \times 10.7 \quad (3)$$

where R_C = respiration rate of okra pods in each cover treatment.

2.4. Temperature and Relative Humidity Monitoring

Air temperatures inside the covering and pulp temperatures at the core of the okra pods were measured using a temperature data logger for air temperature (Tinytag Talk 2: TK-4014-PK, Gemini Data Loggers, West Sussex, UK) with three replications and pulp temperature (Tinytag Talk 2: TK-4023-PK, Gemini Data Loggers, West Sussex, UK) with four replications. Relative humidity inside the covering was recorded using a temperature and relative humidity data logger (Tinytag Ultra 2: TGU-4500, Gemini Data Loggers, West Sussex, UK) at 30 s intervals. Pulp temperature was analyzed using temperature profile and boxplot at 12 h after simulated storage with stable temperature level. After simulated transportation at 30 °C for 15 h, air and pulp temperature levels were analyzed using a boxplot at 1 h 30 min (air temperature of TP at 25 °C) and 15 h after simulation, and the rate of change during temperature rise after simulated transportation was calculated. Data analysis of both air and pulp temperature focused on the data point at 25 °C and temperature range from 25 °C to 30 °C. Furthermore, heatmap analysis represented pulp temperature levels after simulated storage and transportation for 12 h. Python 3.6.9 was used to create the heatmap chart. The packages Seaborn version 0.11.1, Pandas version 1.1.5, and Matplotlib version 3.2.2 were all required by heatmap. The profile of relative humidity throughout the experiment was also investigated.

2.5. Mass Loss Determination

Mass loss of the okra pods was determined using an electric weighing balance (Pioneer^{TM}, Ohaus, NJ, USA). Percentage mass loss (%) was calculated on the basis of initial weight (IW) before cooling and final weight (FW) at the end of simulated storage and transportation, using WL (%) = [(IW − FW/IW] × 100 [30].

2.6. Determination of Decay Incidence

The first sign of okra deterioration was observed as a small wet lesion on pod, and then the entire pod coated with a grayish-white mass of mold. The okra pods were evaluated when incidence of decay occurred, calculated based on weight of pods showing symptoms of decay (D), and classified into four categories, including <10% of decay occurrence, 10–25% of decay occurrence, 25–50% of decay occurrence, and >50% of decay occurrence. Percentage decay (%) was calculated on the basis of total weight of pods per plastic basket (TW), using D (%) = [(D/TW) ×100] [30]. Incidence of decay was determined at the end of simulated storage and transportation.

2.7. Statistical Analysis

SPSS for Windows version 20 (SPSS Inc., Chicago, IL, USA) was used for the statistical analysis. Data analysis for the estimated respiration rate with three replicates, averaged pulp temperature in heatmap chart with four replicates as well as material properties, mass loss, and incidence of decay with five replicates compared by mean at a significant level of 0.05 using Tukey's HSD post hoc test.

3. Results and Discussion

3.1. Materials Properties

The properties of the thermal insulation materials, including thickness, thermal heat energy, WVP, air permeability, and R-value, are shown in Table 2. Temperature transfer through the material was studied in terms of the heat transfer processes. Heat transfer is the process of energy movement caused by temperature differences [20]. Lower thermal heat energy (Q_x) value shows a lower heat transfer rate (good insulator) through the substance layer, while higher Q_x shows a higher heat transfer rate (poor insulator) through the layer [21]. In this study, results indicated that MFS with a thickness of 3.1 mm gave the lowest heat transfer property (Q_x = 1.53 J s^{-1}), compared to the other three materials, while P-LLDPE (0.120 mm) had the highest Q_x value (3.85 J s^{-1}). A combination of HRS (1.450 mm) (2.57 J s^{-1}) and TNNW (0.270 mm) (3.23 J s^{-1}) showed improved insulation property and potential for prototype development for covering material in the future. The high insulation properties of MFS and HRS materials may be partly due to greater thickness. Material with lower thermal heat energy (Q_x) also tends to have a higher R-value. MFS had the highest R-value (0.225 m^2 °C W^{-1}), followed by HRS (0.211 m^2 °C W^{-1}), TNNW (0.187 m^2 °C W^{-1}), and P-LLDPE (0.153 m^2 °C W^{-1}), respectively (Table 2). Results showed that MFS and HRS preserved cool temperatures better than the other materials (Figure 3).

Table 2. Covering material properties (thickness, thermal heat energy, WVP, R-value and air permeability).

Material	Thickness (mm)	Thermal Heat Energy ($Q_x \times 10^{-4}$) (J s^{-1})	R-Value (m^2 °C W^{-1})	Water Vapor Permeability (g h^{-1} m^{-2})	Air Permeability (l m^{-2} s^{-1})
P-LLDPE	0.120 ± 0.03 ^{d}	3.85 ± 0.06 ^{a}	0.153 ± 0.01 ^{d}	0.325 ± 0.04 ^{a}	172.80 ± 12.05 ^{b}
TNNW	0.270 ± 0.20 ^{c}	3.23 ± 0.07 ^{b}	0.187 ± 0.01 ^{c}	0.450 ± 0.05 ^{a}	945.60 ± 43.21 ^{a}
HRS	1.450 ± 0.43 ^{b}	2.57 ± 0.12 ^{c}	0.211 ± 0.02 ^{b}	0.000003 ± 0.00 ^{b}	0.59 ± 0.01 ^{d}
MFS	3.100 ± 0.08 ^{a}	1.53 ± 0.06 ^{d}	0.225 ± 0.01 ^{a}	0.000012 ± 0.00 ^{b}	49.42 ± 0.21 ^{c}

Note: Different letters for different mean levels in each parameter for Tukey's HSD post hoc test indicate significant differences at $p < 0.05$. Values are mean ± S.E. from five replicates. Four materials were perforated linear low-density polyethylene (P-LLDPE), heat-reflective sheet (HRS), thin nonwoven (TNNW), and metalized foam sheet (MFS).

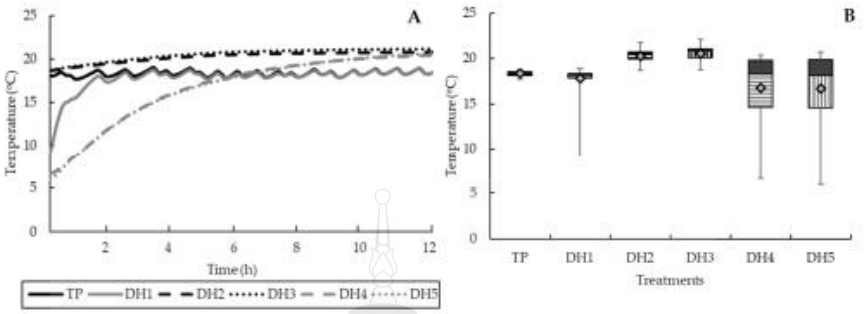


Figure 3. Pulp temperature profiles during simulated storage at 18 °C for 12 h (**A**) and boxplot of pulp temperature profiles during simulated storage at 18 °C for 12 h (**B**). Boxes indicate the lower and upper quartile. The horizontal line in each box represents the median temperature. Mean temperature for each treatment is indicated by ♦. Vertical lines extending above and below each box represent minimum and maximum temperature recorded. Six treatments were no room cooling with P-LLDPE covering (TP as control), room cooling with P-LLDPE covering (DH1), no room cooling with HRS+TNNW covering (DH2), no room cooling with MFS covering (DH3), room cooling with HRS+TNNW covering (DH4), room cooling with MFS covering (DH5).

For water vapor permeability (WVP), a partial pressure difference between the inside and outside of the test material affects the gain or loss of moisture in the product [31]. In this study, TNNW and P-LLDPE showed higher WVP than MFS and HRS, and would be suitable for highly breathable fruits (Table 2). High WVP material had the potential to eliminate vapor condensation, thus inhibiting microbial activity [31]. On the other hand, both MFS and HRS materials had lower WVP values and air permeability, which may cause vapor condensation inside the covering (Table 2). Interestingly, a combination of HRS and TNNW showed good performance in terms of insulation and water and air permeability properties, with the potential to maintain cool temperatures and protect condensation inside the package or cover.

3.2. Respiration Rate, Q_{10} Value, and Heat from Respiration Rate

An increase in storage temperature and time resulted in a rise in okra respiration rate. Respiration rate at three storage conditions (10, 20, 30 °C) for 2 days increased gradually from 186.39 (10 °C) to 355.44 (30 °C) mg CO_2 kg^{-1} h^{-1} as well as on day 3 (Table 3). Similarly, Hardenburg et al. [7] reported that higher storage temperature at 25–27 °C (328–362 mg CO_2 kg^{-1} h^{-1}) increased respiration rate compared to lower temperatures at 5 °C (59 mg CO_2 kg^{-1} h^{-1}) and 10 °C (86 to 95 mg CO_2 kg^{-1} h^{-1}). Furthermore, the widely used Q_{10} value represents an improvement in the rate of a process with a 10 °C increase in temperature [32]. In this study, the Q_{10} value of temperature range (10–20 °C) on days 2 and 3 increased from 1.17 to 1.87, while the Q_{10} value of temperature range (20–30 °C) decreased from 1.50 to 1.37 (Table 3). In lower temperature storage, Q_{10} value is typically less than 2.00 levels, whereas Q_{10} value gradually decreased in higher temperature conditions [33]. However, Q_{10} values of okra during different storage temperatures have never been reported. Yasunaga et al. [34] reported that Q_{10} value of cucumber at 10 to 20 °C was 4.37 and dramatically decreased to 1.89 with higher temperature storage at 20–30 °C. In this study, to estimate okra respiration rate under simulated storage (R_{C1}) and transportation (R_{C2}), the Q_{10} value was calculated for respiration rate in each cover treatment and converted to vital heat as shown in Tables 4 and 5, respectively.

Table 3. Rate of respiration of okra pods at different storage conditions (10, 20, 30 °C) for 2 and 3 days in a closed system.

Temperature (°C)	R_{CO2} (mg CO_2 kg^{-1} h^{-1})		Q_{10}	
	Day 2	Day 3	Day 2	Day 3
10	186.39	207.33		
			1.17	1.87
20	237.70	325.63		
			1.50	1.37
30	355.44	444.61		

Table 4. Estimated respiration rate (R_{C1}) and vital heat among the six treatments under simulated storage at 18 °C for 48 h.

Treatment	Rc_1 (mg CO_2 kg^{-1} h^{-1})	Vital Heat (J kg^{-1} h^{-1})
TP	329 ± 0.0 ^{a}	3522 ± 0.1 ^{a}
DH1	329 ± 0.0 ^{a}	3522 ± 0.1 ^{a}
DH2	330 ± 0.8 ^{a}	3529 ± 8.1 ^{a}
DH3	330 ± 0.9 ^{a}	3536 ± 9.3 ^{a}
DH4	214 ± 0.4 ^{b}	2288 ± 4.7 ^{b}
DH5	218 ± 1.9 ^{b}	2329 ± 20.1 ^{b}

Note: Different letters for different mean levels in each parameter for Tukey's HSD post hoc test indicate significant differences at $p < 0.05$. Values are mean ± S.E. from three replicates. Six treatments were no room cooling with P-LLDPE covering (TP as control), room cooling with P-LLDPE covering (DH1), no room cooling with HRS+TNNW covering (DH2), no room cooling with MFS covering (DH3), room cooling with HRS+TNNW covering (DH4), room cooling with MFS covering (DH5).

Table 5. Estimated respiration rate (R_{C2}) and vital heat among the six treatments under simulated transportation at 30 °C for 1 h (air temperature of TP at 25 °C) and 15 h (the end of simulated transportation).

Treatment	Rc_2 (mg CO_2 kg^{-1} h^{-1}) at 1 h	Vital Heat (J kg^{-1} h^{-1}) at 1 h	Rc_2 (mg CO_2 kg^{-1} h^{-1}) at 15 h	Vital Heat (J kg^{-1} h^{-1}) at 15 h
TP	541 ± 4.7 ^{a}	5791 ± 49.0 ^{a}	640 ± 0.3	6853 ± 3.1
DH1	549 ± 2.6 ^{a}	5873 ± 28.5 ^{a}	646 ± 0.6	6914 ± 6.3
DH2	486 ± 6.1 ^{b}	5202 ± 66.3 ^{bc}	633 ± 4.0	6774 ± 42.5
DH3	483 ± 4.7 ^{b}	5167 ± 49.7 ^{bc}	629 ± 8.2	6732 ± 87.4
DH4	506 ± 2.7 ^{b}	5413 ± 28.0 ^{b}	632 ± 3.2	6768 ± 34.3
DH5	481 ± 8.4 ^{b}	5148 ± 88.4 ^{c}	645 ± 3.8	6900 ± 40.9

Note: Different letters for different mean levels in each parameter for Tukey's HSD post hoc test indicate significant differences at $p < 0.05$. Values are mean ± S.E. from three replicates. Six treatments were no room cooling with P-LLDPE covering (TP as control), room cooling with P-LLDPE covering (DH1), no room cooling with HRS+TNNW covering (DH2), no room cooling with MFS covering (DH3), room cooling with HRS+TNNW covering (DH4), room cooling with MFS covering (DH5).

The efficiency of room cooling and thermal insulation materials under simulated storage and transportation conditions for respiration rate and heat from respiration (vital heat) was studied. Table 4 shows that respiration rates and vital heat levels in DH4 and DH5 were lower than in the other three treatments under simulated storage at 18 °C for 48 h. After room cooling at 0 °C for 2 h, the field heat and vital heat of okra were removed and reduced to around 20% of no room cooling before the cool storage condition. However, no difference was shown between no room cooling plus either P-LLDPE or insulated materials (HRS + TNNW, MFS), as well as room cooling with P-LLDPE. A decrease in vital heat in okra suggested that room cooling combined with insulated material cover should be employed. During simulated transportation at 30 °C for 1 h, the vital heat of DH2, DH3, and DH5 (5148–5202 J kg^{-1} h^{-1}) was lowest compared with TP and DH1, and DH4 treatments (5791 5873 J kg^{-1} h^{-1}). However, at a longer period of simulated transportation

for 15 h, vital heat levels in all DH treatments were similar to TP. The efficiency of thermal insulation materials reduced the vital heat loss for a short period of around an hour. Either room cooling or no room cooling with thermal insulation material covering reduced heat from respiration under heat stress conditions over a short period (Table 5).

3.3. Air and Pulp Temperature Levels of Okra

Room cooling and thermal insulation materials showed efficient cooling under simulated storage and transportation. After simulated storage at 18 °C for 12 h, okra pulp temperature profiles of room cooling treatments (DH1, DH4, and DH5) maintained cool temperature for around 10 h, better than no room cooling treatments (TP, DH2, and DH3). The use of two thermal insulation materials (HRS and MFS) combined with room cooling (DH4 and DH5) maintained cool temperatures, compared to no cover. In addition, the combination of room cooling and thermal insulation as a covering material effectively maintained cool temperature (Figure 3A). Temperature control of cover treatments was presented as a boxplot (Figure 3B) which showed the mean (rhombuses), lowest (lower error bars), and highest temperature (upper error bars) levels. Okra pulp temperature in DH4 and DH5 had the lowest mean temperature (17 °C) compared to the other four treatments (19 °C for TP and DH1; 20 °C for DH2 and DH3). The use of thermal insulation materials without room cooling (DH2 and DH3) gave the significantly highest pulp temperature (highest upper error bars) as well as the warmest level (highest lower error bars) after simulated storage at 18 °C for 48 h. This was presented as a narrow range of cool temperature levels (a smaller boxplot) compared with room cooling (DH4 and DH5) (a larger boxplot).

To simulate actual transportation for 15 h, we designed an experiment to analyze when the air temperature of TP reached a constant level at 25 °C. Thermal insulation materials maintained a cool temperature (average and minimum temperature levels) better, compared to either no covering or covering with P-LLDPE (TP and DH1). However, thermal insulation materials tended to build up pulp temperature (Figure 4C,D). The minimum air and pulp temperatures inside thermal insulation materials were the lowest. (Figure 4A,B). As no published reports were available concerning the effect of room cooling combined with thermal insulation covering under storage and transportation conditions on the quality of okra, the results of this study were compared to published data for other fresh fruits and vegetables. Bollen et al. [35] used low-temperature cooling in combination with pallet covers for asparagus. They found that the use of covering with insulation materials reduced heat generated by fresh produce with high respiratory rates inside the covering. Long-term covering was recognized as a problem due to heat accumulation, leading to a higher temperature than no cover. Other studies reported that thermal insulation covers showed better temperature preservation than no cover, and temperature changes occurred more slowly than with no cover in amaranth [18], strawberries [23], and chard, cucumber, and carrot [24]. However, in this study, both temperature profiles increased to 30 °C within 15 h (Figure 4B,D). Covering with thermal insulation materials maintained cool temperature (<25 °C) under a high-temperature environment for less than 6 h. Additionally, the pulp temperature levels after simulated storage and transportation are presented in the heatmap chart (Figure 5) as a matrix of red–blue color tones with average temperature in each hour for 12 h. At the simulated storage (Figure 5A), DH4 and DH5 had a significantly low average of pulp temperature (blue color tone), while DH2 and DH3 had a significantly high average of pulp temperature (light orange color tone) that related to the highest pulp temperature profiles (Figure 3A) and the smallest boxplot size with the lowest pulp temperature profiles when compared among the five treatments (Figure 3B). Moreover, the heatmap chart during simulated transportation (Figure 5B) showed that the use of thermal insulation materials (DH2, DH3, DH4, and DH5) caused a heat accumulation (light orange color tone) within an hour, then there was no significant difference among all treatments after an hour. The combination of room cooling and thermal insulation materials (DH4 and

DH5) increased the efficiency of maintaining cool temperature more than using thermal insulation materials without room cooling (DH2 and DH3).

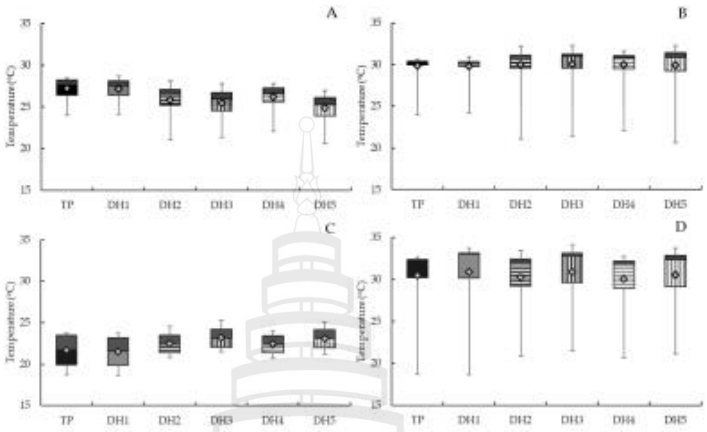


Figure 4. Air temperature profile after 1 h 30 min (**A**) and 15 h (**B**), pulp temperature profile after 1 h 30 min (**C**) and 15 h (**D**) during simulated transportation at 30 °C. An interpretation of the box plot graph is presented as a caption in Figure 3. Six treatments were no room cooling with P-LLDPE covering (TP as control), room cooling with P-LLDPE covering (DH1), no room cooling with HRS+TNNW covering (DH2), no room cooling with MFS covering (DH3), room cooling with HRS+TNNW covering (DH4), room cooling with MFS covering (DH5).

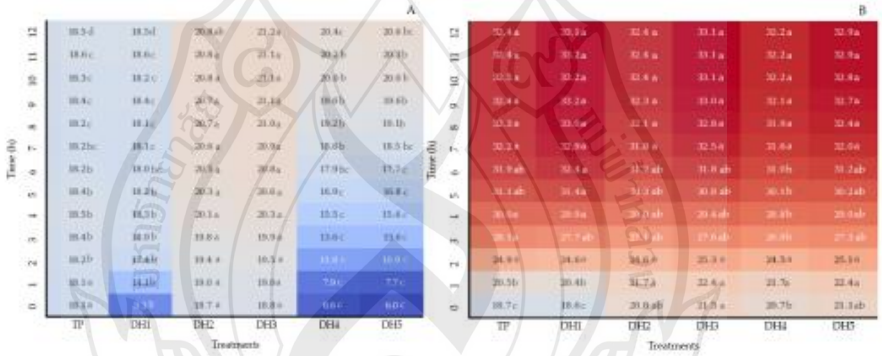


Figure 5. Heatmap chart of pulp temperature profiles during simulated storage at 18 °C for 12 h (**A**) and simulated transportation at 30 °C for 12 h (**B**). Different letters in each row indicate significant differences of mean temperature from four replicates for pulp temperature in each hour at $p < 0.05$. Six treatments were no room cooling with P-LLDPE covering (TP as control), room cooling with P-LLDPE covering (DH1), no room cooling with HRS+TNNW covering (DH2), no room cooling with MFS covering (DH3), room cooling with HRS+TNNW covering (DH4), room cooling with MFS covering (DH5).

Table 6 compares the air temperature change rate inside the covering under simulated transportation testing. TP and DH1 showed the lowest rates of temperature change, whereas no cover in TP and DH1 treatments showed reduced control of cool temperature due to either high air ventilation through the plastic basket or no thermal insulation covering, respectively, indicating the highest thermal heat energy (Q_x) and lowest R-value of

P-LLPPE (Table 2). P-LLDPE gave poor preservation of cool temperature during simulation compared with the other materials. By contrast, low pulp temperature change rate showed high effectiveness of thermal insulation materials (TNNW, HRS, and MFS) for DH2 to DH5 by maintaining cool pulp temperature (Table 6). In previous studies, cardboard in combination with plastic foil of bottle beer gave control cold temperature than hard plastic crate under air temperature condition at 30 °C due to a reduction of the air movement and transferring contribution of the beer bottle as well as a reduction of vibration damping during transportation [36]. The efficiency of a base material nonwoven fabric on temperature-controlled deliveries was studied by Dieckmann et al. [37]. Nonwoven feather fiber composite isolation gave greater material performance aspects than EPS in terms of thermal insulation, and inexpensive, sustainable, and lightweight material. In this study, HRS and MFS-based aluminum foil material and nonwoven performed good thermal insulation. However, the browning incidence of okra pods also caused vibration damage during handling and transportation. Interestingly, further research should be conducted to investigate the combined effects of thermal insulation materials on cold temperature control and vibration damage reduction during transportation.

Table 6. Rate of changes in air and pulp temperature under simulated transportation at 30 °C for 15 h.

Treatment	Rate of Temperature Changes (°Ch^{-1})			
	Air Temperature		Pulp Temperature	
	T_1–25 °C	25–30 °C	T_1–25 °C	25–30 °C
TP	7.54 ± 0.17 ^{b}	1.40 ± 0.02 ^{a}	4.26 ± 0.20 ^{a}	2.64 ± 0.15 ^{a}
DH1	7.34 ± 0.21 ^{b}	1.40 ± 0.01 ^{a}	4.00 ± 0.11 ^{a}	2.58 ± 0.02 ^{ab}
DH2	9.56 ± 0.47 ^{ab}	1.13 ± 0.04 ^{b}	2.55 ± 0.08 ^{b}	2.02 ± 0.05 ^{bc}
DH3	10.30 ± 1.41 ^{ab}	1.32 ± 0.05 ^{a}	2.50 ± 0.08 ^{b}	1.88 ± 0.15 ^{c}
DH4	11.69 ± 0.47 ^{a}	1.14 ± 0.03 ^{b}	2.59 ± 0.10 ^{b}	1.83 ± 0.08 ^{c}
DH5	9.25 ± 0.45 ^{ab}	1.08 ± 0.04 ^{b}	2.75 ± 0.18 ^{b}	1.75 ± 0.15 ^{c}

Note: T_1 is the temperature at the end of the simulated storage. Different letters in different mean levels of each parameter for Tukey's HSD post hoc test indicate significant differences at $p < 0.05$. Values are mean ± S.E. from five replicates. Six treatments were no room cooling with P-LLDPE covering (TP as control), room cooling with P-LLDPE covering (DH1), no room cooling with HRS+TNNW covering (DH2), no room cooling with MFS covering (DH3), room cooling with HRS+TNNW covering (DH4), room cooling with MFS covering (DH5).

3.4. Relative Humidity inside Covering Materials

Relative humidity was monitored during simulated storage and transportation. Relative humidity of TP and DH1 as no covering (75%) (Figure 6A) was lower than all the other thermal insulation materials (100% RH) (Figure 6B,C) after storage for 48 h. This showed that the use of thermal insulation materials for covering preserved relative humidity fluctuation inside the covering was better than without covering (Figure 6B,C). Low relative humidity in TP and DH1 increased mass loss (>15%), while thermal insulation covers with 100%RH reduced mass loss (5%) throughout this simulation (Figure 7). The effect of relative humidity (RH) on the quality of 'Niitaka' pears was studied by Lim et al. [38] using two types of pallet covers made of polyethylene film to maintain high RH in commercial low-temperature storage rooms. Use of pallet covers increased RH from 83 to 87% or 93 to 95% for open and closed pallet covers, respectively. Moreover, using insulated material for covering preserved the relative humidity inside the covering and was better than no covering during shipping delays in amaranth [18]. Covering with thermal insulation materials maintained the highest RH level (100% RH) after 12 h, particularly HRS and MFS (Figure 6). This result related to the lowest WVP level of HRS and MFS materials, which preserved the relative humidity inside the covering (Table 2). On the other hand, low WVP of MFS caused condensation inside the covering and accelerated the activity of microorganisms with an increase of decay incidence (Figure 8).

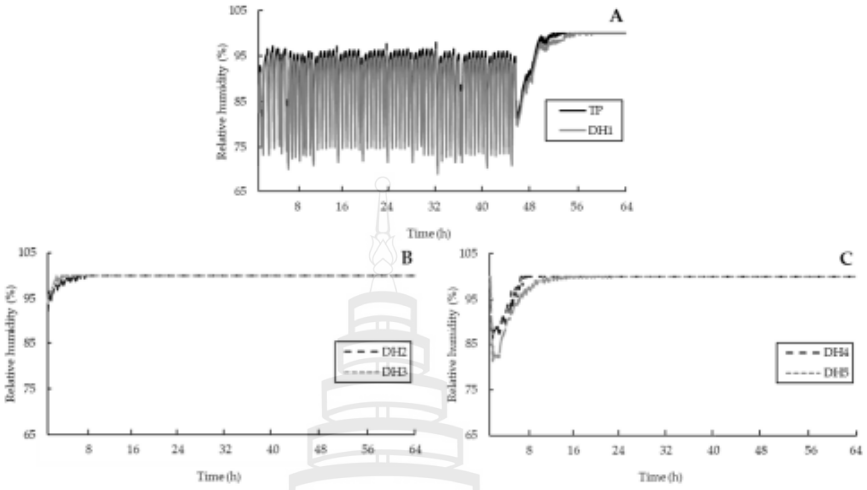


Figure 6. Relative humidity profiles among treatments, including TP and DH1 (**A**), DH2 and DH3 (**B**), DH4 and DH5 (**C**), after simulated storage at 18 °C for 48 h and simulated transportation at 30 °C for 15 h. Six treatments were no room cooling with P-LLDPE covering (TP as control), room cooling with P-LLDPE covering (DH1), no room cooling with HRS+TNNW covering (DH2), no room cooling with MFS covering (DH3), room cooling with HRS+TNNW covering (DH4), room cooling with MFS covering (DH5).

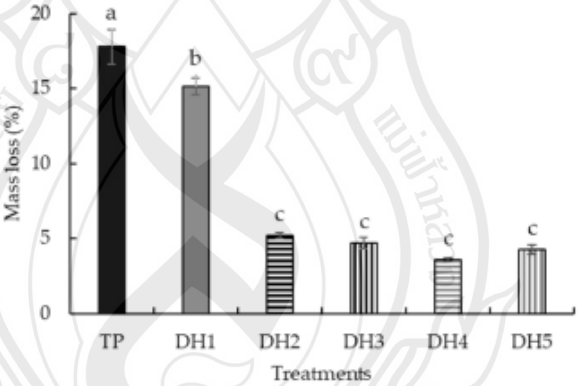


Figure 7. Mass loss (%) among the six treatments after simulated storage at 18 °C for 48 h and simulated transportation at 30 °C for 15 h. Different letters in different mean levels of each parameter for Tukey's HSD post hoc test indicate significant differences at $p < 0.05$. Values are mean ± S.E. from five replicates. Six treatments were no room cooling with P-LLDPE covering (TP as control), room cooling with P-LLDPE covering (DH1), no room cooling with HRS+TNNW covering (DH2), no room cooling with MFS covering (DH3), room cooling with HRS+TNNW covering (DH4), room cooling with MFS covering (DH5).

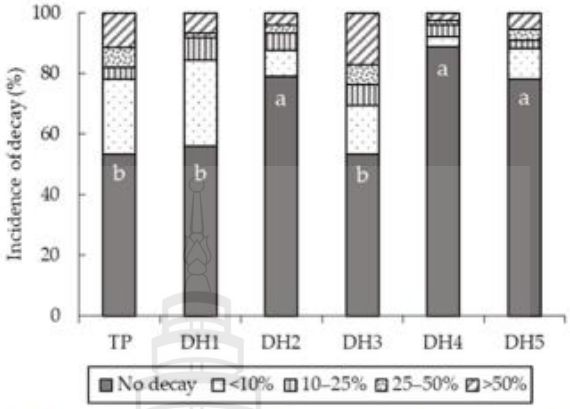


Figure 8. Incidence of decay (%) among the six okra treatments after simulated storage at 18 °C for 48 h and simulated transportation at 30 °C for 15 h. Different letters in different mean levels of each parameter for Tukey's HSD post hoc test indicate significant differences at $p < 0.05$. Values are mean ± S.E. from five replicates. Six treatments were no room cooling with P-LLDPE covering (TP as control), room cooling with P-LLDPE covering (DH1), no room cooling with HRS+TNNW covering (DH2), no room cooling with MFS covering (DH3), room cooling with HRS+TNNW covering (DH4), room cooling with MFS covering (DH5).

3.5. Mass Loss of Okra

Okra pods in TP and DH1 (no cover and P-LLDPE covering) lost a significant amount of fresh weight (around 15%) compared to thermal insulation material treatments (5%) (Figure 7). This corresponded to better performance in maintaining lower temperature and higher relative humidity by thermal insulation materials (Figures 3 and 6). There was no significant difference between room cooling or no cooling combined with thermal insulation materials (Figure 7). However, limited data exist comparing the efficiency of thermal insulation covering on mass loss of fresh produce. Wheeler et al. [18] reported that amaranth contained in uncovered pallets had more weight (11.0%) than in pellets covered with Reflectix™ insulation material (2.0%) (bubble pack insulation consisted of reflective aluminum foil and heavy gauge polyethylene) over a 6 h storage cycle. Reflectix™ cover effectively minimized the amount of moisture loss during amaranth storage. Macnish et al. [39] compared the performance of four propriety pallet cover systems (CO_2 West, PEAKfresh, PrimePro, and Tectrol) in maintaining the quality of strawberry fruit during transportation with a temperature at 20 °C. Results showed that pallet cover systems significantly reduced transport-related mass loss by less than 0.5%, compared to those with control or no cover material (0.8%). Similarly, Lim et al. [38] found that the use of pallet cover in pear storage for 7 days reduced mass loss compared to no pallet cover. The application of pallet cover is an alternative technique for controlling temperature and humidity fluctuation during transportation [40] as well as reducing the rate of mass loss [41]. In this study, low mass loss of okra in thermal insulation covers after simulation (Figure 7) was related to low levels of WVP (Table 2).

3.6. Incidence of Decay (ID)

Highly significant decay of okra at 50–80% was presented in no room cooling plus covering with either thermal insulation material or P-LLDPE. The okra pods turned black with mold infection. The DH4 and DH5 treatments had the lowest percentage of ID (<20%) compared to the other four treatments (Figures 8 and 9). Thermal insulation materials maintained cool temperature and relative humidity (Figures 3 and 6). This was related

to a lower incidence of decay (Figure 8) and mass loss (Figure 7). Increasing efficiency of thermal insulation covers suggested application with room cooling to maintain a cool temperature under heat stress conditions. However, the application of MFS covering should be considered in case of a high-temperature condition (30 °C) over 15 h, which may lead to heat accumulation (Figure 4). Vapor condensation resulted in an increase of okra decay (Figure 8) due to low WVP (Table 2). Thermal insulation covers may be applied for a short journey (<6 h) for domestic transportation under ambient temperature (no refrigerated vehicle) to maintain cool temperature with less decay. HRS+TNNW covering with cooling technique showed high potential application for fresh produce with high respiration rates, such as asparagus, broccoli, mushroom, and sweet corn [29]. The overall post-harvest loss from mass loss and incidence of decay showed that TP was the highest post-harvest loss (65%), followed by DH1 (59%), DH3 (52%), DH5 (27%), DH2 (26%), and DH4 (15%), respectively (Figures 7 and 8).

Figure 9. Okra pictures from the six treatments including TP (**A**), DH1 (**B**), DH2 (**C**), DH3 (**D**), DH4 (**E**), and DH5 (**F**) after simulated storage at 18 °C for 48 h and simulated transportation at 30 °C for 15 h. Six treatments were no room cooling with P-LLDPE covering (TP as control), room cooling with P-LLDPE covering (DH1), no room cooling with HRS+TNNW covering (DH2), no room cooling with MFS covering (DH3), room cooling with HRS+TNNW covering (DH4), room cooling with MFS covering (DH5).

4. Conclusions

Room cooling with TNNW provided greater efficiency to preserve a cool temperature (2 °C) and reduce the decay of okra (10%), compared to TP (42%) and no room cooling plus MFS (48%) after simulated cool storage and high-temperature transportation conditions. Application of thermal insulation materials for covering reduced mass loss (5%), compared to either no cover or P-LLDPE throughout the simulation test (15–17%). Thus, the room cooling combined with HRS+TNNW (DH4) gave the lowest post-harvest loss (15%) as compared to TP, cooling plus P-LLDPE (DH1), and no cooling plus MFS (DH3) in a range of post-harvest loss (52% to 65%). Results showed that cooling was a very important step to apply in the post-harvest handling of okra before covering to remove both field heat and respiratory heat. Material properties, including low thermal heat energy (Q_x) level and high R-value and WVP value, should be considered for developing thermal insulation material for fresh produce. Future research should be conducted to assess the effect of room cooling and thermal insulation material for other fresh fruits and vegetables, particularly the high respiration rate group.

Author Contributions: J.R. conducted experiments, analyzed data, interpretated results, and assisted manuscript writing. R.S. co-investigated, interpretated results, and assisteddata analysis. C.P. co-investigated, supported cover materials, interpretated results in material analysis, and assisted manuscript writing. H.K. provided comments and suggestions for the final draft of the manuscript. S.C. was the principal investigator of the research, responsible for the overall research management,

interpretation of results, and manuscript writing. All authors have read and agreed to the published version of the manuscript.

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References

1. Tripathi, K.K.; Govila, O.P.; Warrier, R.; Ahuja, V. Biology of *Abelmoschus esculentus* L. (Okra). In *Series of Crop Specific Biology Documents*; Department of Biotechnology, Ministry of Science & Technology & Ministry of Environment and Forest, Govt. of India: New Delhi, India, 2011; 26p.
2. Thai Customs. Statistic Report 2020. 2020. Available online: http://www.customs.go.th/statistic_report.php?lang=en&tariff_code=07099990003 (accessed on 14 August 2020).
3. Tsado, E.K. Quality of postharvest handling of marketable okra fruits sold in Minna, Niger State, Nigeria. *Eur. J. Agric. For. Res.* **2015**, *3*, 33–45.
4. Okra: Postharvest Care and Market Preparation; Publications in the Postharvest Handling Technical Bulletin Series No.10. 2003. Available online: http://agriculture.gov.gy/wp-content/uploads/2016/01/Okra.pdf (accessed on 10 November 2020).
5. Perkins-Veazie, P.; Collins, J.K. Cultivar, packing and storage temperature differences in postharvest shelf life of okra. *HortTechnogy* **1992**, *2*, 350–352. [CrossRef]
6. Taain, D.A.; Jasim, A.M.; Al-Hij, M.J.H.H. A study of storage behavior of okra fruits (*Abelmoschus esculuntus* L. Moenth cv. Khnesri). *Int. J. Farming Allied Sci.* **2014**, *3*, 760–766.
7. Okra: The Commercial Storage of Fruits. Vegetables and Florist and Nursery Stocks. USDA-ARS Agriculture Handbook #66 (Revised). 2016. Available online: https://www.ars.usda.gov/arsuserfiles/oc/np/commercialstorage/commercialstorage.pdf (accessed on 10 November 2020).
8. Cheng, Z.; Gong, X.; Jing, W.; Peng, Z.; Li, J. Quality change of postharvest okra at different storage temperatures. *J. Food Eng. Technol.* **2018**, *7*, 43.
9. Kader, A.A. *Postharvest Technology of Horticultural Crops*, 3rd ed.; University of California Agriculture and Natural Resources: Davis, CA, USA, 2002; pp. 39–47.
10. Huang, S.; Li, T.; Jiang, G.; Xie, W.; Chang, S.; Jiang, Y.; Duan, X. 1-Methylcyclopropene reduces chilling injury of harvested okra (*Hibiscus esculentus* L.) pods. *Sci. Hortic.* **2012**, *141*, 42–46. [CrossRef]
11. Saltveit, M.E. Measuring Respiration. 2015. Available online: http://ucce.ucdavis.edu/files/datastore/234-20.pdf (accessed on 10 June 2020).
12. Kienholz, J.; Edeogu, I. *Fresh Fruit and Vegetable Pre-Cooling for Market Gardeners in Alberta*; Alberta Agriculture, Food and Rural Development: Edmonton, AB, Canada, 2002; pp. 1–4.
13. Food and Agriculture Organization of the United Nations (FAO). *Good Practice in the Design Management and Operation of a Fresh Produce Packing-House*; FAO Region Office for Asia and the Pacific: Bangkok, Thailand, 2012; pp. 44–47.
14. Dhall, R.K.; Sharma, S.R.; Mahajan, B.V.C. Development of post-harvest protocol of okra for export marketing. *J. Food Sci. Technol.* **2014**, *51*, 1622–1625. [CrossRef] [PubMed]
15. Yang, Z.; Ma, Z.; Zhao, C.; Chen, Y. Study on forced-air pre-cooling of Longan. In *2007 ASAE Annual Meeting 076267, Minneapolis, MN, 17–20 June 2007*; American Society of Agricultural and Biological Engineers: St. Joseph, MI, USA, 2007.
16. Wang, Z.; Chen, L.; Yang, H.; Wang, A. Effect of exogenous glycine betaine on qualities of button mushrooms (*Agaricus bisporus*) during postharvest storage. *Eur. Food Res. Technol.* **2015**, *240*, 41–48. [CrossRef]
17. Deshmukh, G.; Birwal, P.; Datir, R.; Patel, S. Thermal insulation materials: A tool for energy conservation. *J. Food Process Technol.* **2017**, *8*, 670. [CrossRef]
18. Wheeler, L.; Kitinoja, L.; Barrett, D. Use of insulated covers over product crates to reduce losses in amaranth during shipping delays. *Agriculture* **2015**, *5*, 1204–1223. [CrossRef]
19. Singh, S.P.; Burgess, G.; Singh, J. Performance comparison of thermal insulated packaging boxes, bags and refrigerants for single-parcel shipments. *Packag. Technol. Sci.* **2008**, *21*, 25–35. [CrossRef]
20. Harding, K.G. *Heat Transfer Introduction*; University of the Witwatersrand: Johannesburg, South Africa, 2018; pp. 1–62.

21. Harvey, B.V. Mild Chilling Injury of Banana (Cavendish cv. *Williams*) and Its Control in the Field. Ph.D. Thesis, The University of Adelaide, Adelaide, Australia, September 2005.
22. Desjarlais, A.O.; Zarr, R.R. (Eds.) *Insulation Materials, Testing and Applications, 4th Volume (Vol. 1426)*; ASTM International: West Conshohocken, PA, USA, 2002; 417p.
23. Chaiwong, S.; Bishop, C.F.H. Use of an insulated bag from the supermarket to maintain 'Elsanta' strawberry temperature to households. *Acta Hortic.* **2014**, *1079*, 187–192. [CrossRef]
24. Melis, R.B. New Techniques and Methods for Cold Chain Monitoring and Tracking in Perishable Products. Ph.D. Thesis, Universidad Politécnica de Madrid, Madrid, Spain, 2016; pp. 134–146.
25. Liu, Y.B. Low-temperature phosphine fumigation of chilled lettuce under insulated cover for postharvest control of western flower thrips, *Frankliniella occidentalis* (Pergande) (*Thysanoptera: Thripidae*). *J. Asia Pac. Entomol.* **2011**, *14*, 323–325. [CrossRef]
26. ASTM. *(96). Standard Test Methods for Water Vapor Transmission of Materials*; ASTM International: West Conshohocken, PA, USA, 2005.
27. ASTM. *Standard Test Method for Air Permeability of Textile Fabrics*; D737-96; ASTM International: West Conshohocken, PA, USA, 1996; pp. 230–234.
28. Kader, A.A.; Saltveit, M.E. Respiration and gas exchange. *Post. Physio. Patho. Veg.* **2003**, *2*, 7–29.
29. Patel, B.B.; Roy, P.S.; Saiyad, M.J.S.; Joshi, D.C. Respiration behaviour and heat of respiration of mango (cv. *Langdo*) under different storage conditions. *Int. J. Agric. Environ. Biotechnol.* **2016**, *9*, 855–859. [CrossRef]
30. Ngure, J.W.; Aguyoh, J.N.; Gaoquiong, L. Interactive effects of packaging and storage temperatures on the shelf-life of okra. *ARPN J. Agric. Biol. Sci.* **2009**, *4*, 43–52.
31. Mangaraj, S.; Goswami, T.K.; Panda, D.K. Modeling of gas transmission properties of polymeric films used for MA packaging of fruits. *J. Food Sci. Technol.* **2015**, *52*, 5456–5469. [CrossRef] [PubMed]
32. Tripathi, P.C.; Lawande, K.E. Temperature-related changes in respiration and Q_{10} coefficient in different varieties of onion. *Progress. Hortic.* **2010**, *42*, 88–90.
33. Murata, S.; Miyauchi, K.; Wang, Y. Measurement of respiration of fresh vegetables. *J. Jpn. Soc. Agric. Mach.* **1993**, *55*, 69–75.
34. Yasunaga, E.; Tomita, K.; Hamanaka, D.; Hu, W.; Uchino, T. Effect of temperature on the respiration rate of some vegetables. *IFAC Proc. Vol.* **2001**, *34*, 205–210.
35. Bollen, F.; Bycroft, B.L.; Brash, D.W. Using insulation and cooling to improve the asparagus cool chain. *Acta Hortic.* **1993**, *415*, 323–332.
36. Paternoster, A.; Van Camp, J.; Vanlanduit, S.; Weeren, A.; Springael, J.; Braet, J. The performance of beer packaging: Vibration damping and thermal insulation. *Food Packag. Shelf Life* **2017**, *11*, 91–97. [CrossRef]
37. Dieckmann, E.; Nagy, B.; Yiakoumetti, K.; Sheldrick, L.; Cheeseman, C. Thermal insulation packaging for cold-chain deliveries made from feathers. *Food Packag. Shelf Life* **2019**, *21*, 100360. [CrossRef]
38. Lim, B.S.; Lim, C.I.; Gross, K.C. High relative humidity under pallet coverage maintained 'Niitaka' pear fruit (*Pyruspyrifolia Nakai*) quality during low temperature storage. *Korean J. Hortic. Sci. Technol.* **2005**, *23*, 135–139.
39. Macnish, A.J.; Padda, M.S.; Pupin, F.; Tsouvaltzis, P.I.; Deltsidis, A.I.; Sims, C.A.; Brecht, J.K.; Mitcham, E.J. Comparison of pallet cover systems to maintain strawberry fruit quality during transport. *HortTechnology* **2012**, *22*, 493–501. [CrossRef]
40. Mourch, J.; Laguerre, O.; Flick, D.; Commere, B. Analysis of use of insulating pallet covers for shipping heat sensitive foodstuffs in ambient conditions. *Comput. Electron. Agric.* **2002**, *34*, 89–109. [CrossRef]
41. Badia-Melis, R.; Mc Carthy, U.; Ruiz-Garcia, L.; Garcia-Hierro, J.; Villalba, J.R. New trends in cold chain monitoring applications-A review. *Food Control* **2018**, *86*, 170–182. [CrossRef]

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Performance of Thermal Insulation Covering Materials to Reduce Postharvest Losses in Okra

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Abstract: The efficiency of different thermal insulation covers in minimizing temperature fluctuations in cool chain management was investigated to reduce postharvest loss and maintain okra quality during storage and transportation. The four thermal insulation covering materials: (1) heat reflective sheet with thin nonwoven (HRS + TNNW), (2) heat reflective sheet with thick nonwoven (HRS + TKNW), (3) metalized Tyvek® (MTyvek) and (4) metalized foam sheet (MFS) were studied and compared with perforated linear low-density polyethylene (P-LLDPE) as the typical handing package for okra distribution alongside no covering as the control. The material properties, transpiration rate, vital heat, temperature profiles (air and pulp temperatures), relative humidity, mass loss and incidence of decay were determined throughout a simulated supply chain. Results exhibited that HRS + TNNW and HRS + TKNW covers had the lowest thermal heat energy (Q_k) and moderate R-value. These two covers maintained low temperature fluctuation with the lowest rate of air and pulp temperature changes, reflecting in lowest mass loss and decay in okra. The HRS + TNNW cover yielded less decay (1%) in okra, compared to commercial covers; MTyvek (16%) and MFS (9%). Results showed that HRS + TNNW exhibited great potential as a thermal insulation cover to reduce postharvest loss in okra (5%) compared to typical handling (11–18%) and could be considered as alternative material to reduce the use of foam sheets in cool chain management distribution packaging of okra under ambient environment conditions.

Keywords: cool chain management; covering material; nonwoven; metalized foam sheet

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1. Introduction

Okra (*Abelmoschus esculentus* L.) belongs to the Abelmoschus genus of the Malvaceae family [1]. Okra is an economic vegetable crop grown in Thailand and exported to global markets, especially Japan, Hong Kong, Switzerland, Germany and the United Arab Emirates. Japan is the main importer of fresh okra from Thailand (worth approximately 5.50 million USD) per annum and accounts for 82.6% of the total exported okra volume [2]. Concerns in okra production, including fruit quality determination, inadequate harvesting procedures, okra harvester training levels, lack of suitable transportation and insufficient pre-cooling facilities, have all been cited as problems for marketable okra [3].

Optimal storage conditions of okra to extend shelf-life from 7 to 10 days range from 7 to 10 °C with a relative humidity (RH) 95 to 100% [4]. Higher temperatures than 25 °C result

in unmarketable quality and a shorter shelf-life of 3 days [5–7]. At high temperature, okra is susceptible to water loss, color fading and rotting with consequent loss of commercial value [8]. Okra has a high respiration rate, therefore, temperature is the most significant environmental factor affecting the postharvest quality. Increase in storage temperature to 25–27 °C resulted in an elevated respiration rate (328–362 mg CO_2 kg^{-1} h^{-1}) compared with a lower temperature storage at 4–5 °C (53–95 mg CO_2 kg^{-1} h^{-1}) [4]. Mass losses of okra at 5 °C, 10 °C and 25 °C after 5 days storage were 10%, 16% and 27%, respectively [5].

Cool chain management is an end-to-end controlled temperature process used to preserve the quality of commodities throughout the supply chain [9]. Cool chain management prevents biological decay and ensures the delivery of healthy, high-quality foods to customers. The optimal storage temperature range for fruits and vegetables is 0 to 16 °C [10]. Several studies have investigated cooling and storage cold chain management of okra [4,5,7,11–13]. For heat removal after harvesting, forced-air cooling was recommended for the handling of exported okra [14]. In India, room cooling at 15 °C was applied to exported okra before storage at 8 °C [15]. Recently, room cooling at 0 °C for 2 h was applied in combined with usage of thermal insulation covering materials, to reduce decay incidence and mass loss of okra in Thailand [16].

Material properties including thickness, number of surfaces and number of reflective surfaces are important factors that determine insulating ability of the materials [17]. The most common thermal insulation materials used for pallet cover applications such as polystyrene, aluminum foil and nonwoven fabrics were described in terms of material properties, particularly thermal conductivity. A lower thermal conductivity that restricted heat transfer provided improved thermal insulation property [18]. Polystyrene foam and polyurethane have the lowest thermal conductivity of the possible materials used, followed by nonwoven fabrics or polypropylene. Aluminum foil is a reflective insulation material composed of one or more low-emission surfaces that provides high thermal conductivity and reflects heat to effectively minimize heat radiation [19]. Aluminum foil as pallet cover material is used on its own and combined with expanded polyethylene (EPE) as foam sheet for fresh produce covering [20].

Thermal insulation packaging minimizes the rate of temperature change and is used for up to 50% of chilled food [21]. Investigations have been extensively undertaken on thermally insulated packaging boxes for food delivery and pallet covers for fresh produce during distribution and transportation [18,20,22,23]. Pallet covers are used as packaging to minimize waste from food spoilage by delaying rapid changes of temperature and humidity in amaranth [20], chard, cucumber, carrot [22], and strawberry [23]. However, limited studies have addressed the positive impacts of pallet covers in reducing postharvest loss of fresh fruits and vegetables. Previous research studies have addressed thermal insulation covering of fresh fruits and vegetables, but no reports are available for okra or other high respiration rate crops. Most previous studies of thermal insulation coverings on fresh produce only focused on controlling temperature, with no examination of fresh produce quality. Recently, the first report on thermal insulation packaging of fresh produce was done to evaluate efficiency of thermal insulation covering materials combined with room cooling for controlling temperature fluctuation and reduction of postharvest mass loss and decay of okra. Results suggested that room cooling at 0 °C for 2 h for heat removal was important before covering with thermal insulation materials. Combined room cooling with two-layer heat reflective sheet with thin nonwoven (HRS + TNNW) as a developing handling exhibited the highest efficiency for preserving cool temperature and reducing postharvest loss of okra (mass loss and decay) (15%) compared to typical handling (no room cooling and covering) (65%), covering with perforated linear low-density polyethylene (59%) and metalized foam sheet (MFS) (27%). Furthermore, the difference in postharvest loss between no room cooling and room cooling observed in HRS + TNNW and MFS treatments were 11% and 25%, respectively. This indicated that room cooling plays an important role in maintaining the okra quality as a pretreatment before covering with thermal insulation material [16].

According to domestic transportation of okra from community enterprise in Phayao province (in the northern part of Thailand) to food factories (in the central part of Thailand), high temperature and relative humidity fluctuations in transportation vehicles caused postharvest losses of okra such as wilting heat damage and decay. Poor cooling facilities, including no pre-cooling, no cooling storage and non-refrigerated vehicle during transportation, all caused physiological loss. Losses of perishable crops due to a lack of refrigeration were higher in developing countries (23%) than in developed countries (9%) [24]. In this study, a prototype of thermal insulation covering was designed by combining materials between heat reflective sheet and thin nonwoven (HRS + TNNW) as an alternative to foam-based material to minimize okra postharvest losses and transportation cost. The objectives of this study were: (1) to investigate the performance of different thermal insulation covering materials in controlling temperature fluctuations under storage and transportation temperature conditions, and (2) to evaluate the reduction of postharvest loss and the quality of okra, when covered with thermal insulation materials.

2. Materials and Methods

2.1. Determination of Material Properties

Thermal insulation materials employed for covers were perforated linear low-density polyethylene (P-LLDPE), thin nonwoven (TNNW), thick nonwoven (TKNW), heat reflective sheet (HRS), metalized Tyvek® (MTyvek) and metalized foam sheet (MFS). Their thermal properties as rate of heat energy (Q_x), R-value, water vapor permeability (WVP) and air permeability were determined. Six replicates were tested and average values were reported.

Equipment settings and thermal heat energy measurements were performed following the procedure of Harvey [25] and our previous research [16]. Briefly, rate of thermal heat energy (Q_x) was determined as the rate at which heat energy passed through the material by using two expanded polystyrene (EPS) boxes with a hole (10 × 10 cm^2) between two chambers. Temperature data loggers (Tinytag Talk 2: TK-4014-PK, Gemini Data Loggers, Chichester, West Sussex, UK) were used to monitor the temperature change between the two chambers for 3 h until constant, and the transfer rate of thermal heat energy (Q_x) in J s^{-1} unit was calculated.

Water vapor permeability (WVP) was examined for different insulation materials using the desiccant in cup method. Following ASTM96 [26], the specimen or cover material (20 cm^2) was sealed to the open mouth of a test dish containing a desiccant and placed in a constant climate chamber (KBF-115, Binder, Tuttlingen, Germany) at 25 °C with 50% relative humidity (RH). WVP was calculated as rate of water vapor transmission in g h^{-1} m^{-2} unit. Air permeability was determined using an air permeability tester (FX 3300 LabAir IV, Textest Instruments, Schwerzenbach, Switzerland) according to ASTM D737-04 [27]. The thermal insulation materials were cut into 20 × 20 cm^2 squares and results were reported in L m^{-2} s^{-1} unit.

The R-value was calculated as resistance to heat flow through the thermal insulation material using the ice-melt procedure of Singh et al. [18]. To calculate the melt rate, the weight of water was reported as m^2 °C W^{-1} unit using Equation (1):

$$\text{System R-value} = (\text{Surface area} \times \text{Temperature difference})/(\text{Melt rate} \times \text{Latent heat}) \quad (1)$$

where, surface area is inside surface area of the thermal insulation cover (m^2), temperature difference (°C) is ambient temperature − - melting point of ice (25 °C − 0 °C = 25 °C), melt rate (kg h^{-1}) is weight of water collected divided by test time, latent heat is 335 kJ kg^{-1}.

2.2. Plant Materials and Treatments

'Lady Finger' okra pods were harvested around 45 days after planting or 6 days after flowering (September 2019) from the okra plantation (latitude 20°13′27.2″N longitude 99°50′05.2″E) in Mae Chan district, Chiang Rai Province, Thailand. The okra pods (5 kg) were carefully transferred into 10 kg plastic baskets to protect against bruising or abrasion

from the farm to the Postharvest Laboratory (S7) at Mae Fah Luang University within 30 min. After arrival at the laboratory, okra pods were graded for size uniformity with pod length of 7 to 11 cm (specific size for okra processing) and sorted according to minimum requirements; fresh, green in color, free distinct signs of bruising, smooth and clean at pedicel cut surface. The okra pods (1500 g) were packed in plastic baskets for room cooling treatment for 2 h by setting the cooling medium at 0 °C. The pulp temperature of okra was monitored, using a multichannel data logger (Hioki, LR8431, Nagano, Japan) connected with a type-K thermocouple for 10 channels (plastic baskets), to check uniformity of pulp temperature during room cooling treatment. The final pulp temperature of packed okra in all baskets reached 9 °C after room cooling for 2 h. After cooling, the okra pods were packed in six treatments of different insulation materials (four treatments and P-LLDPE), including no cover as a control.

Six treatments with five replicates included five covering materials; P-LLDPE, HRS + TNNW, HRS + TKNW, MTyvek and MFS (Figure 1) with size of 18 × 32 × 12 cm^3, compared with control (no cover). The HRS material was evenly perforated with a pin of diameter 0.55 mm to give total perforation area of 0.09 cm^2. Two layers of covers as HRS + TNNW and HRS + TKNW were prepared by attaching HRS and NW via spot bonding (Figure 2). Following the postharvest handling of okra from community enterprise in Phayao province, all six treatments were transferred to simulated storage at 18 ± 2 °C for 48 h, followed by simulated transportation. at 30 ± 1 °C for 15 h.

Figure 1. Five insulation materials as treatments.

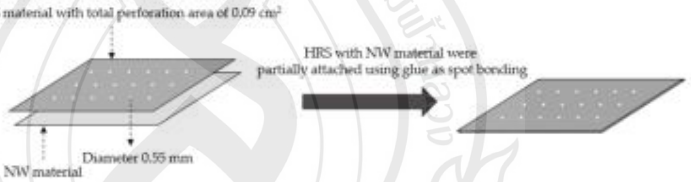

Figure 2. Function design of the combination between HRS and NW materials.

2.3. Determination of Air and Pulp Temperature in Okra

Air and pulp temperatures inside the okra pod were measured at 30 s intervals from the start of cooling using two types of temperature data loggers; air temperature (Tinytag Talk 2: TK-4014-PK, Gemini Data Loggers) with three replicates and pulp temperature (Tinytag Talk 2: TK-4023-PK, Gemini Data Loggers, Chichester, West Sussex, UK) with four replicates. Percentage RH level was determined by a temperature and relative humidity data logger (Tinytag Ultra 2: TGU-4500, Gemini Data Loggers, Chichester, West Sussex, UK) at intervals of 30 s.

Measured air and pulp temperatures were analyzed using a boxplot at 12 h after simulated storage and transportation. Rates of temperature changes (°C h^{-1}) during temperature rise after cooling to 25 °C for temperature ranges of 25 °C to 30 °C were calculated. Median value temperatures were presented as boxplots and included accumulated time-temperature (ATT) (°C h) throughout the simulated supply chain. Heatmap analyses representing air and pulp temperature levels during 12 h after simulated storage

and transportation were presented. Heatmap visualizations were created using MATLAB Software version R2018a (MathWorks Inc., Natick, MA, USA) in this study.

For thermal imaging, temperatures were immediately recorded by a thermal camera (FLIR ONE® Pro LT, Teledyne FLIR, Wilsonville, OR, USA) after removing the cover to provide a rapid visual comparison at the end of simulated transportation.

2.4. Determination of Respiration Rate and Vital Heat

The rate of okra respiration was measured in a closed system, as shown in Figure 3. The details of the test set up were described elsewhere in our previous study [16]. Briefly, the okra pods (150 g) were packed in a plastic food container (8400 mL) under three storage temperature conditions (10, 20, 30 °C) with a range of 70–90% RH with three replicates in each condition. Gas was sampled for CO_2 detection at day 2 (48 h) and day 3 (72 h) and analyzed by a gas chromatograph (GC) (7890A, Agilent Technologies, Santa Clara, CA, USA). Respiration rate (R_c) for respiration was calculated to unit of mL CO_2 kg^{-1} h^{-1} and converted to mg CO_2 kg^{-1} h^{-1} by multiplying conversion figure at 10 °C (1.89), 20 °C (1.83) and 30 °C (1.77) by Equation (2) [28,29]. The temperature coefficient (Q_{10}) was calculated by Equation (3) [30]:

$$R_c \text{ (mg } CO_2 \text{ kg}^{-1} \text{ h}^{-1}) = (\%CO_2 \times V)/(100 \times FW \times T) \quad (2)$$

where, CO_2 is the concentration of CO_2 gas (%), V is volume of container (mL), FW is fruit weight (kg) and T = closing time (h):

$$Q_{10} = (R_2/R_1)^{10/(T_2 - T_1)} \quad (3)$$

where, R_2 and R_1 are the respiration rate at temperature T_2 and T_1, respectively.

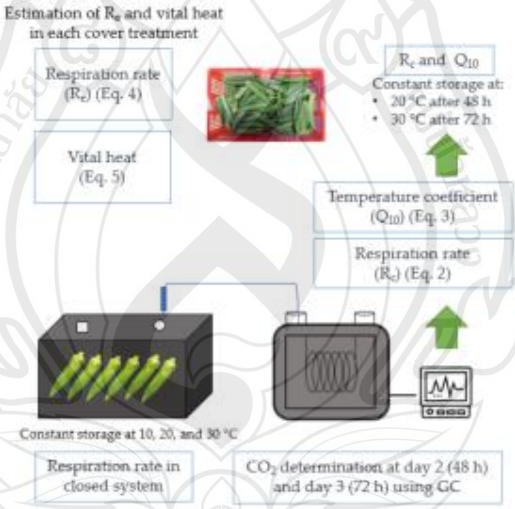

Figure 3. Determination of respiration rate and vital heat.

The calculated Q_{10} values on day 2 (48 h) and day 3 (72 h) (Table 1) were then employed to estimate the respiration rate of okra pods (R_e) at various air temperature levels inside different covers and no cover. Air temperatures in either covers or no cover were recorded using a temperature data logger (Tinytag Talk 2: TK-4014-PK, Gemini Data Loggers, Chichester, West Sussex, UK) under simulated storage (18 °C for 48 h) and transportation (30 °C for 15 h) temperature conditions. The air temperature level for estimation of

okra respiration rate (R_e) in each cover treatment was determined from the median air temperature after simulated storage and transportation (Section 2.3). Respiration rates (R_c) at 20 °C after 48 h and at 30 °C after 72 h were used to estimate okra respiration rate under simulated storage and transportation (Section 2.3). Estimated respiration rates of okra among treatments were calculated using Equation (4):

$$R_e = R_c \times Q_{10}^{(T_2 - T_1)/10} \quad (4)$$

where, R_e is the estimated respiration rate of okra in each cover or no cover, R_c is the respiration rate from closed system, T_2 is the final air temperature after simulation, and T_1 is the initial air temperature before simulation.

Table 1. Okra respiration rate in a closed system after three storage conditions at (10, 20 and 30 °C) for 2 and 3 days.

Temperature (°C)	R_c (mg CO_2 kg^{-1} h^{-1})		Q_{10}	
	Day 2	Day 3	Day 2	Day 3
10	183.33	195.26		
			1.40	1.51
20	245.11	276.68		
			1.37	1.46
30	333.15	399.05		

A heat production (2.55 cal) from respiration is calculated by a CO_2 production of 1 mg. A respiration rate of 1 mg CO_2 kg^{-1} h^{-1} indicates a heat production of 61.2 kcal ton^{-1} day^{-1}. In this study, vital heat from respiration of okra was calculated and converted into a unit of J kg^{-1} h^{-1} from kcal ton^{-1} day^{-1} in Equation (5) [31]:

$$\text{Vital heat (J kg}^{-1}\text{ h}^{-1}) = R_e \times 10.7 \quad (5)$$

2.5. Determination of Transpiration Rate

The transpiration rate was calculated from the mass of okra pods using an electric weighing balance (Pioneer™, Ohaus, Parsippany, NJ, USA). Initial mass before cooling and final mass at the end of storage simulation (18 °C for 48 h) and transport simulation (30 °C for 15 h) were determined. Transpiration rate was calculated per unit of surface area (TR_A) in g h^{-1} m^{-2}, given by Equation (6) [32]:

$$TR_A = (m_i - m_t)/(t \times A) \quad (6)$$

where, m_i is the initial fruit mass (g), m_t is the mass of fruit at time (g), t is time (h) and A is the surface area of the fruit (m^2).

Surface area of the okra pod was calculated by Equation (7) [33]:

$$S = \pi D_g^2 \quad (7)$$

where, S is surface area (m^2) and D_g is geometric mean.

The geometric mean of okra was estimated calculation for the cylindrical nature of okra pod shape (Figure 4) by Equation (8) [33]:

$$D_g = \sqrt[4]{L \times W^2} \quad (8)$$

where, L is length (m) and W is width (m).

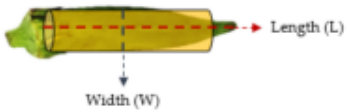

Figure 4. Geometry of an okra pod shape.

2.6. Mass Loss Determination

Mass loss of okra pods was determined using an electric weighing balance (Pioneer™, Ohaus). Percentage mass loss (%) was calculated on the basis of initial weight (IW) before cooling and final weight (FW) at the end of simulated storage (18 °C for 48 h) and simulated transportation (30 °C for 15 h) by the equation WL (%) = [(IW − FW/IW] × 100.

2.7. Incidence of Decay

The decay of okra pods was described in four categories as <10% of decay occurrence, 10–25% of decay occurrence, 25–50% of decay occurrence and >50% of decay occurrence. The initial decay symptom exhibited tissue damage containing a small-soaked lesion or the whole pod covered up with a grayish-white mass of mold. The okra pods of each decay symptom were categorized and weighed (D). The percentage decay (%D) in each category was determined on the basis of total weight per plastic basket of pods after storage at 18 °C for 48 h (TW) using; D (%) = [(D/TW) × 100] [34]. Incidence of decay was determined at the end of simulated transportation.

2.8. Statistical Analysis

SPSS for Windows version 20 (SPSS Inc., Chicago, IL, USA) was used for statistical, correlation and cluster analyses. Data analyses for material properties, transpiration rate, vital heat, rate of temperature change, mass loss rate and incidence of decay among the six treatments were compared by mean ($\alpha = 0.05$) using Tukey's HSD test. All data variables among six treatments were analyzed using Pearson correlation analysis at the 0.01 level. Material properties, transpiration rate, vital heat, rate of air and pulp temperature changes, accumulated time-temperature, mass loss and incidence of decay from the six treatments were determined as clustering analysis using Ward's coefficient by agglomerative hierarchical clustering.

3. Results and Discussion

3.1. Materials Properties

Properties of covering materials including thickness, Q_x, R-value, WVP and air permeability were shown in Table 2. P-LLDPE (thickness of 0.120 mm) having low insulation property exhibited the highest thermal heat energy value (Q_x) of 3.750×10^{-4} J s^{-1}, while MPS (thickness of 3.100 mm) with high insulation property exhibited the lowest thermal heat energy (1.440×10^{-4} J s^{-1}). A high R-value of material indicates high insulation property that relates to low thermal heat energy value. Highest R-value of MPS was 0.223 m^2 °C W^{-1} followed by HRS (0.214 m^2 °C W^{-1}), MTyvek (0.208 m^2 °C W^{-1}), TKNW (0.194 m^2 °C W^{-1}), TNNW (0.181 m^2 °C W^{-1}) and P-LLDPE (0.161 m^2 °C W^{-1}). Heat transmission played a role in temperature transfer and material property that explained the performance of temperature preservation by material covers [22,35]. Heat transfer can be defined as the transmission of energy that results in a temperature differential [35]. Thermal heat energy (Q_x) and R-value variables were the principal thermal insulation qualities in this investigation (Table 2). Highest insulation property was observed in MPS that had the lowest thermal heat energy as well as the highest R-value, while MTyvek and HRS materials had lower Q_x and greater R-value levels than the two nonwovens of different thicknesses (TKNW and TNNW). Regarding thermal heat energy (Q_x), lower Q_x level indicated lower heat transfer rate (good insulator) through the material layer [25]. In thermal insulation material applications, the thickness of materials (conduction), the bulk

movement of fluids (heat transfer between solid and fluid) (convection) [35], and number of reflective surfaces (radiation) affect the insulating ability [17]. The thermal insulation material prototype was designed as HRS combined with either TNNW (0.270 mm) or TKNW (0.470 mm) to increase insulation property. Developing a thermal insulation material for okra package cover improved more conduction by increasing nonwoven thickness, convection by increasing the number of layer materials and reflective surface by applying HRS with nonwoven material.

Table 2. The properties of six covering materials (thickness, thermal heat energy, WVP, R-value and air permeability).

Material	Thickness (mm)	Thermal Heat Energy ($Q_x \times 10^{-4}$) (J s^{-1})	R-Value (m^2 °C W^{-1})	Water Vapor Permeability (g h^{-1} m^{-2})	Air Permeability (L m^{-2} s^{-1})
P-LLDPE	0.131 ± 0.20 ^{e}	3.750 ± 0.07 ^{a}	0.161 ± 0.00 ^{d}	0.360 ± 0.03 ^{a}	172.801 ± 5.85 ^{b}
TNNW	0.282 ± 0.10 ^{d}	3.255 ± 0.04 ^{b}	0.181 ± 0.00 ^{c}	0.373 ± 0.11 ^{a}	917.000 ± 64.27 ^{a}
TKNW	0.478 ± 0.28 ^{c}	3.148 ± 0.00 ^{b}	0.194 ± 0.00 ^{c}	0.0083 ± 0.00 ^{b}	168.623 ± 21.70 ^{b}
HRS	1.445 ± 0.02 ^{b}	2.368 ± 0.15 ^{c}	0.214 ± 0.01 ^{b}	0.000002 ± 0.00 ^{d}	0.543 ± 0.07 ^{d}
MTyvek	0.127 ± 0.03 ^{e}	2.947 ± 0.02 ^{bc}	0.208 ± 0.00 ^{b}	0.00057 ± 0.00 ^{c}	0.497 ± 0.03 ^{d}
MFS	3.109 ± 0.01 ^{a}	1.440 ± 0.06 ^{d}	0.223 ± 0.01 ^{a}	0.000008 ± 0.00 ^{d}	45.503 ± 4.20 ^{c}

Note: Different letters indicate significant differences at $p < 0.05$. Values are mean ± S.E. from six replicates.

In terms of water vapor permeability (WVP), the partial pressure difference between inside and outside of the test material impacts moisture gain or loss in the product [36]. From results, TNNW (0.373 g h^{-1} m^{-2}) and P-LLDPE (0.360 g h^{-1} m^{-2}) provided higher WVP than MFS (0.000008 g h^{-1} m^{-2}) and HRS (0.000002 g h^{-1} m^{-2}) (Table 2). Similarly, WVP of LLDPE-based nanocomposite films ranged from 0.07 to 0.31 g h^{-1} m^{-2} [37], and higher than WVP of aluminum foil (0.009 mm) (0.00042 to 0.00051 g h^{-1} m^{-2}) [38]. Using high WVP materials gives potential to eradicate vapor condensation, thus reducing microbial activity [36]. Air permeability through TNNW sheet was the highest (917.000 L m^{-2} s^{-1}), while those through HRS (0.543 L m^{-2} s^{-1}) and MTyvex (0.497 L m^{-2} s^{-1}) were the lowest. MFS and HRS materials had low WVP and air permeability values (Table 2), resulting in vapor condensation inside the covers. A designed combination of perforated HRS with either TNNW or TKNW provided good thermal insulation, water and air permeability and highest overall thermal insulation properties to maintain lower air and pulp temperature levels (Figure 5) without moisture condensation inside the cover.

3.2. *Temperature and Relative Humidity Inside Cover Materials*

In postharvest handling, application of insulation packaging for fresh produce to preserve cool temperature requires cooling treatment before covering. The efficiency of controlling low temperature was analyzed and presented as a box plot graph (Figure 5). The means (rhombus symbol) of air and pulp temperature levels inside HRS + TNNW, HRS + TKNW, MTyvek and MFS treatments (range of pulp temperature (15.5 °C) and range of air temperature (16.8 °C)) during simulated storage at 18 °C for 12 h were lower than both no cover and P-LLDPE treatments (range of pulp temperature (16.5 °C) and range of air temperature (17.2 °C)) (Figure 5A). Pulp temperature control with low fluctuation was shown by the large size of boxplot. No cover and P-LLDPE treatments exhibited a narrow range of cool air temperature (smaller boxplot) compared with the other four thermal insulation covers (HRS + TNNW, HRS + TKNW, MTyvek and MFS) (larger boxplots) under simulated storage (Figure 5A,B). During simulated storage at 18 °C for 12 h, lower air and pulp temperature levels observed in these four thermal insulation treatments corresponded to their lower Q_x values and higher R-values, compared to no cover and P-LLDPE treatments (Table 2). After transferring to a higher temperature (simulated transportation), MTyvek maintained lower mean air and pulp temperatures (29.5 °C and 27.8 °C) than the other five treatments (no cover at 30.9 °C and 27.3 °C, P-LLDPE at 30.7 °C and 29.5 °C, HRS + TNNW at 30.8 °C and 29.9 °C, HRS + TKNW at 30.5 °C and 29.5 °C and

MFS at 30.2 °C and 28.8 °C) as shown in Figure 5B,D. In commercial practice, maximum temperature inside Tyvek cover of asparagus reduced by 8–9 °C compared to no cover [39].

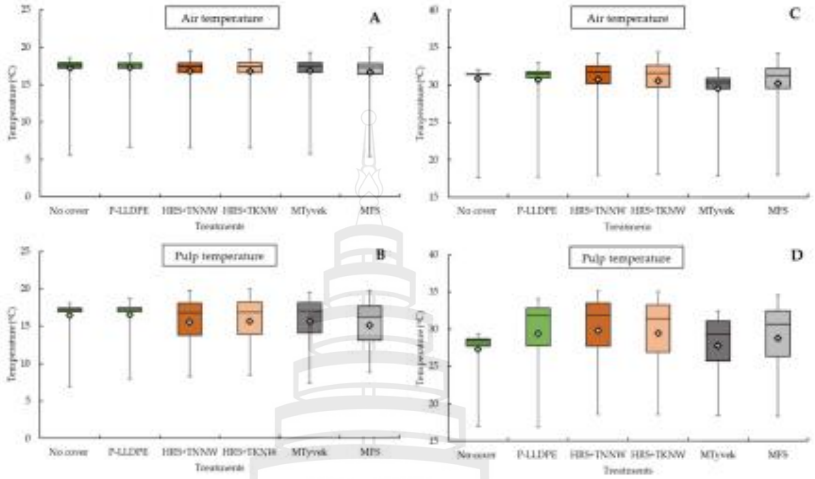

Figure 5. Boxplot of air (**A**) and pulp (**B**) temperature profiles during simulated storage at 18 °C for 12 h. Air (**C**) and pulp (**D**) temperature profiles during simulated transportation at 30 °C for 12 h. The lower and upper quartiles are represented by boxes. The horizontal line represents the median temperature in each box while the mean temperature is indicated by (◊). Minimum and maximum temperatures are presented by vertical lines extending above and below each box.

In this study, good temperature control during simulated transportation (Figure 5C,D) was associated with lower rates of changes in air and pulp temperatures in the four thermal insulation treatments (Table 3). The no cover treatment showed the highest rates of air and pulp temperature changes at all conditions (T_1 to 25 °C and 25 °C to 30 °C), compared to P-LLDPE and the four thermal insulation treatments. This indicated that covering with either P-LLDPE or thermal insulation materials reduced temperature changes under both simulation conditions (Table 3). These findings further support the idea of Liu [40] study. A typical double-bubble foil insulation sheet with 97% heat reflectance and a very low heat conductivity was applied to phosphine fumigation in chilled lettuce. The average rate of temperature change was 0.173 °C h^{-1}. The rise in temperature was only 2.7 °C at the end of the 18 h fumigation treatment at the start of the fumigation (4.5 °C).

Table 3. Rates of air and pulp temperature change in six treatments under 15 h of simulated transportation at 30 °C.

Treatment	Rate of Temperature Change(°C h^{-1})			
	Air Temperature		Pulp Temperature	
	T_1 to 25 °C	25 °C to 30 °C	T_1 to 25 °C	25 °C to 30 °C
No cover	18.94 ± 1.20 ^{a}	14.05 ± 2.48 ^{a}	5.38 ± 0.04 ^{a}	3.27 ± 0.28 ^{a***}
P-LLDPE	16.11 ± 1.19 ^{ab}	4.70 ± 0.44 ^{b}	4.21 ± 0.24 ^{b}	2.72 ± 0.15 ^{ab}
HRS + TNNW	13.35 ± 1.94 ^{bc}	2.66 ± 0.63 ^{b}	3.36 ± 0.04 ^{c}	2.50 ± 0.23 ^{ab}
HRS + TKNW	11.41 ± 0.14 ^{bc}	2.17 ± 0.38 ^{b}	3.02 ± 0.23 ^{cd}	2.33 ± 0.09 ^{b}
MTyvek	11.15 ± 1.02 ^{bc}	1.46 ± 0.30 ^{b}	2.72 ± 0.05 ^{d}	1.27 ± 0.13 ^{c}
MFS	9.26 ± 0.65 ^{c}	2.17 ± 0.51 ^{b}	2.91 ± 0.06 ^{cd}	1.92 ± 0.14 ^{bc}

Note: Different letters indicate significant differences at $p < 0.05$. Values are mean ± S.E. from three (air temperature) and four (pulp temperature) replicates. *** It is noted that no cover treatment was estimated temperature at 28 °C due to the maximum pulp temperature level at air temperature at 30 °C.

A high rate of temperature change in no cover and P-LLDPE, observed during simulated storage and transportation, was in good agreement with heatmap results that exhibited a matrix of red-blue color tones from 0 to 35 °C during each hour for 12 h testing (Table 3 and Figure 6). In both simulated storage and transportation conditions, no cover and P-LLDPE treatments exhibited higher air temperature than the other four cover treatments (Figure 6A,C), while the other four thermal insulation covers exhibited lower pulp temperature than no cover and P-LLDPE within 6 h for simulated storage (Figure 6B). No cover and MTyvek presented a light orange color tone, indicating lower average air and pulp temperatures during simulated 12 h-transportation compared with the other four treatments (Figure 6C,D). These heatmap results were corresponding well with results of thermal imaging that illustrated purple tone color (representing a low pulp temperature) after simulated transportation at 30 °C for 15 h (immediate removal covering) (Figure 7). This implied that both no cover and MTyvek treatments had higher air ventilation and heat transfer from inside the cover to the environment under simulated transportation. Therefore, the thermal image technique could be considered as an additional rapid technique to monitor the temperature. When temperature assessment is conducted on metalized sheet material, awareness of the camera emissivity setting [22] as well as the impacts of high emissivity coatings and orientation of the readings are important [41].

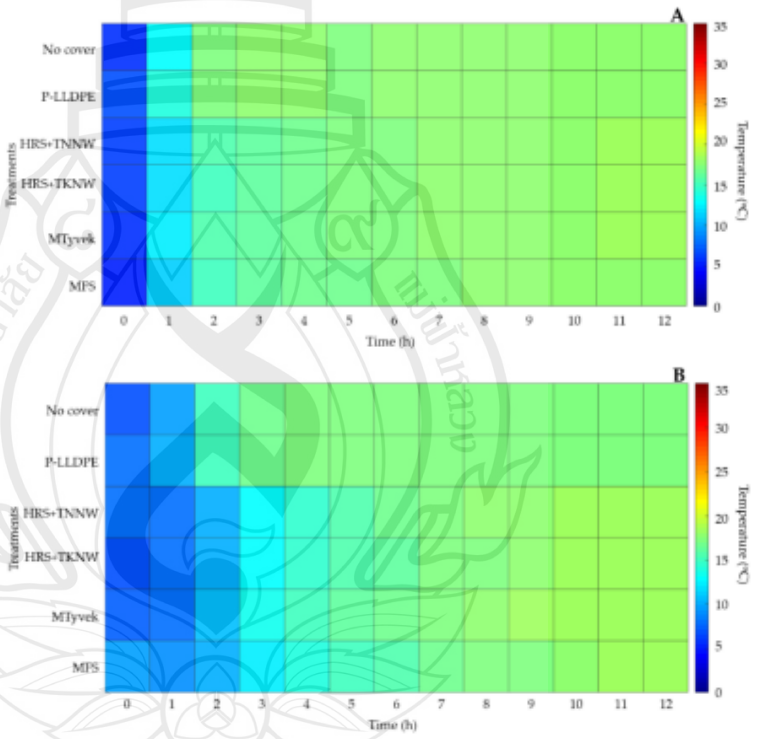

Figure 6. *Cont.*

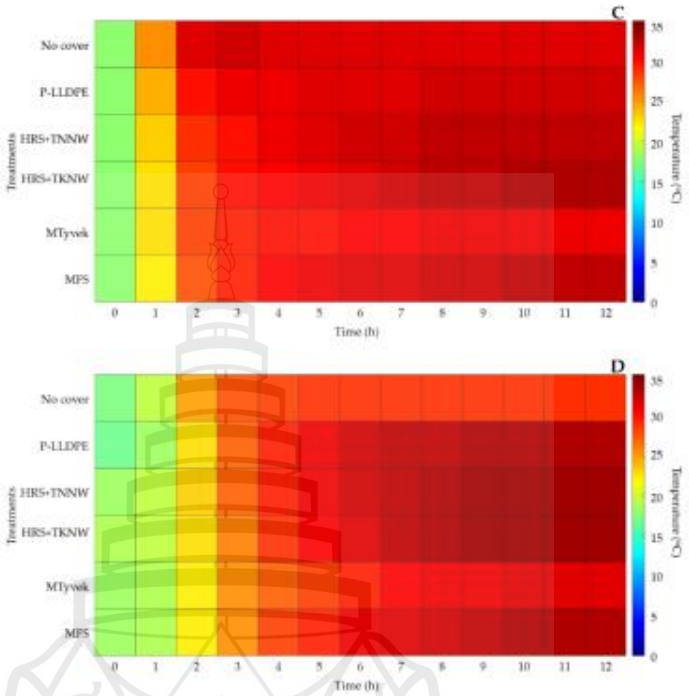

Figure 6. Heatmap chart of air (**A**) and pulp (**B**) temperature profiles during simulated storage at 18 °C for 12 h. Air (**C**) and pulp (**D**) temperature profiles during simulated transportation at 30 °C for 12 h.

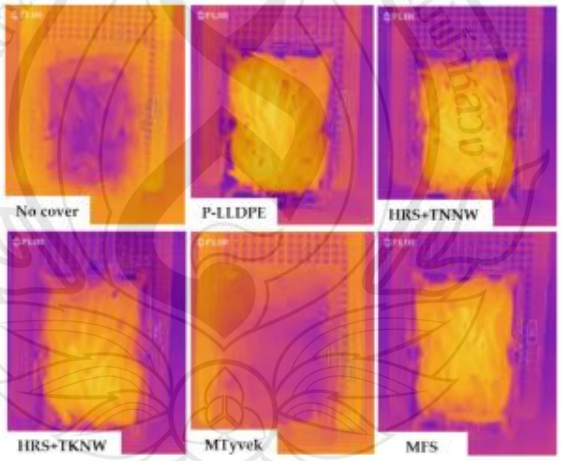

Figure 7. Thermal imaging among the six treatments represented pulp temperature after finishing simulated transportation at 30 °C for 15 h (removal covering). Purple and orange color zones represent cool and warm temperature gradients, respectively.

HRS + TKNW treatment exhibited the highest accumulated time-temperature (ATT) of 1396.4 °C h followed by MFS (1373.4 °C h), MTyvek (1357.8 °C h), P-LLDPE (1337.1 °C h) and no cover (1297.0 °C h) (Figure 8). The use of thermal insulation covers containing aluminum sheet (HRS + TNNW, HRS + TKNW and MFS) over 7 h resulted in greater heat accumulation inside the cover, caused by the high respiration of okra compared with no cover and P-LLDPE treatments (Figures 5–7). Similarly, our previous study showed that thermal insulation materials (HRS + TNNW and MFS) tended to build up pulp temperature of okra under simulated transportation at 30 °C for 15 h [16]. This result was consistent with Bycroft et al. [42] who recommended that long-term covering of asparagus should be reconsidered due to higher heat accumulation compared to no cover.

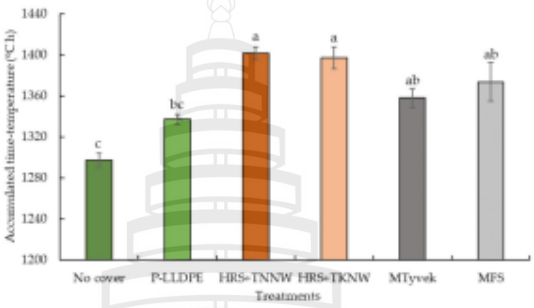

Figure 8. Accumulated time-temperature (ATT) (°C h) among the six treatments after simulated storage at 18 °C for 48 h and simulated transportation at 30 °C for 15 h. Different letters indicate significant differences at $p < 0.05$. Values are mean ± S.E. from four replicates.

From the results, it was suggested that application of a thermal insulation cover for okra (high respiration rate crops) under high temperature (25 °C) should be less than 7 h to avoid increased heat accumulation. Application of frozen gel pack helped to reduce temperature rise of food products (chicken salad and Brie cheese) inside Mylar foil bags under stress temperature at 37 °C [43]. Thus, placement of frozen gel packs is recommended inside thermal insulation covers to maintain low temperature under condition of extremely high temperature. Future study on applying thermal insulation covering in other high respiration rate crops and the use of gel packs or gel phase change materials (PCMs) should also be considered, while investigating the reduction in browning or blackening from mechanical damage under actual or simulated transportation would also be beneficial.

Scant research has been conducted on thermal insulation covers in okra or other high respiration rate crops. This study aimed to evaluate and assess thermal insulation covers in okra as a representative of high respiratory crops. The use of aluminum-based materials in combination with either nonwoven or expanded polyethylene (EPE) materials focused on developing thermal insulation covers (Table 2). Overall results on air and pulp temperatures inside the four thermal insulation covers gave improved performance and maintained low temperature profiles and fluctuation than no cover and P-LLDPE cover treatments (Figures 5, 6 and 8, Table 3). Materials with lower Q_x value and higher R-value exhibited higher efficiency in maintaining low air and pulp temperatures (Table 2). Few studies on other fresh produce identified the positive effect of thermal insulation covers in controlling the inside cool temperature. The insulated pallet cover Reflectix™ constructed of aluminum foil and 0.8 cm polyethylene/bubble pack reduced mass loss in amaranth with less wilting and retained the desirable dark green leaf color [20], In strawberry, Tyvek®, a flash-spun nonwoven high-density polyethylene maintained cool temperature and prevented quality loss from supermarket to household refrigerator [23]. Insulation pallet coverings (Tyvek®, metalized PET, metalized PET bubbles) have provided greater temperature retention compared to no covering in chard, cucumber and carrot [22]. Recently, our previous study showed that application of thermal insulation covering

(HRS + TNNW and MFS) in combined with room cooling (17 °C) could maintain the lowest mean pulp temperature, compared to P-LLDPE and no cover (19 °C) under simulated storage at 18 °C for 48 h [16]. Most academic reports revealed that application of different commercial covers yielded greater performance of thermal insulation compared to no cover but only a few studies have compared material function design of different commercial covers. In this study, commercial HRS material was perforated using a pin of diameter 0.55 mm to give total perforation area of 0.09 cm^2. Two layers of either HRS + TNNW and HRS + TKNW were partially attached using glue as spot bonding. These designed insulation materials possessed moderate Q_x and R-value and exhibited good performance in controlling low temperature, heatmap profiles, thermal images and rate of temperature changes compared to commercial MFS that had the lowest Q_x and highest R-value levels (Tables 2 and 3, Figures 5–7).

The optimal relative humidity (%RH) for storage of okra at 95 to 100% extended shelf-life by 7 to 10 days [4]. Application of thermal insulation covers reduced relative humidity fluctuation better than no cover throughout simulated storage and transportation conditions. Covering maintained RH level at 100% RH after both simulated conditions for 8 h (Figure 9). Stability of RH level under thermal insulation materials was related to low WVP of the materials. Similarly, our previous study found that thermal insulation covering prevented RH fluctuation better than no covering, resulting in the highest RH level at 100% RH [16]. In this study, MFS cover treatment provided the lowest WVP level (Table 2). It had been reported that RH level inside Tyvek® cargo cover at 50% RH (high water vapor permeability) was lower than aluminum bubble wrap with 80% RH (lower water vapor permeability) [44]. However, limited academic research has focused on the application of thermal insulation materials for maintaining relative humidity. Lim et al. [45] investigated the effect of relative humidity (RH) on the quality of 'Niitaka' pears using polyethylene (PE) film pallet covers to maintain high RH in commercial low temperature storage rooms. When opened, the PE pallet cover had a lower RH level (83 to 87%) than when closing PE (93 to 95% RH), while Wheeler et al. [20] discovered that RH level in clamshells packed in both covered and uncovered pallets increased to almost 100% RH within one hour of storage and remained high throughout the storage duration (6 h).

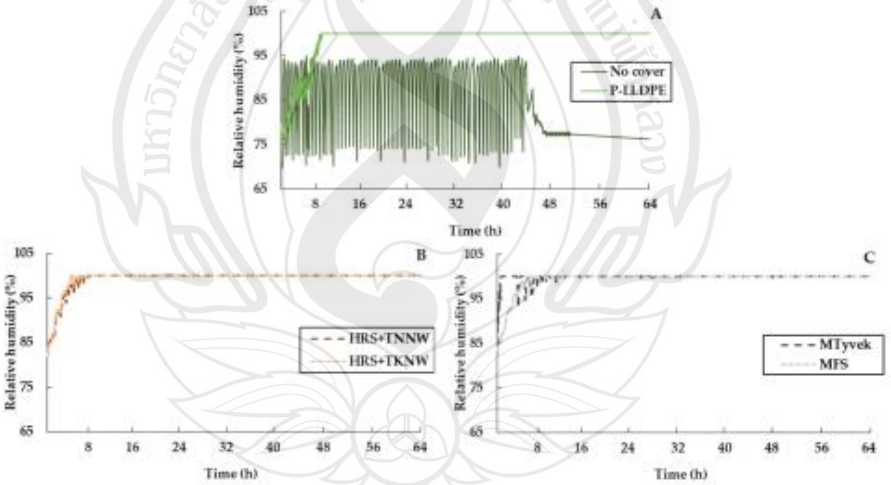

Figure 9. Relative humidity (% RH) profiles among the six treatments of no cover and P-LLDPE (**A**), HRS + TNNW and HRS + TKNW (**B**) and MTyvek and MFS (**C**) after simulated storage at 18 °C for 48 h and simulated transportation at 30 °C for 15 h.

3.3. Transpiration Rate and Vital Heat from Respiration in Different Covers

The transpiration rate and vital heat of okra under the six treatments were measured during simulated storage at 18 °C for 48 h and simulated transportation at 30 °C for 15 h. The major contribution of mass loss in pear and pomegranate was due to transpiration rather than respiration [32,46]. In this study, differences among the six treatments were observed in transpiration rate compared to vital heat under both simulated storage and transportation conditions. This implied that thermal insulation materials influenced transpiration rate (mass loss) more than vital heat from respiration rate (Figure 10). During simulated storage, no cover and P-LLDPE provided the highest transpiration rates (12.53 and 15.56 g h^{-1} m^{-2}, respectively), compared to the other four cover treatments. Under increased temperature during simulated transportation, transpiration rate of all six treatments increased gradually to more than double compared to okra under simulated storage. Highest transpiration rate was found in no cover as the control (35.11 g h^{-1} m^{-2}) followed by P-LLDPE (16.85 g h^{-1} m^{-2}), MTyvek (15.76 g h^{-1} m^{-2}), MFS (9.06 g h^{-1} m^{-2}) HRS + TNNW (9.05 g h^{-1} m^{-2}) and HRS + TKNW (8.53 g h^{-1} m^{-2}) (Figure 10A). This indicated that increase in temperature inside the four thermal insulated cover treatments had less effect on transpiration rate compared to no cover and P-LLDPE treatments. A study on P-LLDPE cover material by Rattanakaran et al. [47] revealed that transpiration rate of okra at 25 °C was greater than at 5 °C (5.16 and 1.93 g h^{-1} m^{-2}, respectively) after 48 h of testing. Lower transpiration rates in thermal insulation treatments related to their lower WVP, except for TNNW. Lowest transpiration rates of HRS and MFS materials related to the lowest WVP levels (Figure 10 and Table 2). The double layer of HRS + TNNW protected the transpiration rate of okra (Figure 10A).

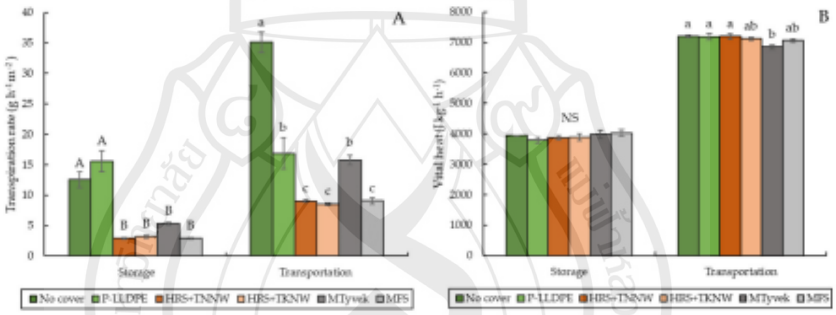

Figure 10. Transpiration rate (**A**) and vital heat (**B**) among the six treatments during simulated storage at 18 °C for 48 h and simulated transportation at 30 °C for 15 h. Different letters indicate significant differences at $p < 0.05$. Values are mean ± S.E. from five replicates.

During simulated storage, no significant difference in vital heat was observed among the six treatments. In this study, MTyvek (6850 J kg^{-1} h^{-1}) exhibited the lowest vital heat level compared with the other five treatments during simulated transportation at 30 °C for 15 h with no difference among P-LLDPE, HRS + TNNW and MFS covers (Figure 10B). Our results confirmed previous findings of Rattanakaran et al. [16]. The vital heat of okra inside thermal insulation cover (HRS + TNNW and MFS) was lower than that inside P-LLDPE at 30 °C for 1 h, while HRS + TNNW exhibited a lower vital heat than MFS and P-LLDPE at 30 °C for 15 h as simulated transportation. In this study, the box plot of MTyvek showed the lowest mean, median and maximum pulp temperature levels during simulated transportation compared with the other treatments, except for no cover (Figure 5). The thermal image of MTyvek exhibited a blue color, similar to the no cover treatment, whereas the other thermal insulation covers showed an orange color (Figure 7) due to higher heat transfer to the environment as well as improved air ventilation in MTyvek than in the other thermal insulation covers.

3.4. Mass Loss of Okra

After simulated storage, okra pods in no cover and P-LLDPE treatments showed significant mass loss of fresh weight at 5–6% compared to those of the other four thermal insulation material treatments (approximately 1%). Similarly, after simulated transportation, no cover showed the highest percentage of mass loss (14.4%) followed by P-LLDPE (7.1%), MTyvek (6.6%), HRS + TNNW (3.7%), HRS + TKNW (3.4%) and MFS (3.6%). Combined HRS with nonwovens and MFS treatments gave lower mass loss than MTyvek (2%), P-LLDPE (3.5%) and no cover (11%) (Figure 11). Similarly, HRS + TNNW and MFS had the lowest mass loss of okra (<5%) compared to P-LLDPE (15%) throughout simulated storage and transportation [16]. High mass loss observed in no cover and P-LLDPE treatments corresponded to high transpiration rates (Figure 10A), high rates of air and pulp temperature changes (Table 3) and low relative humidity levels (Figure 9). Scant research has addressed how thermal insulation covers can be applied to reduce mass loss in fresh fruits and vegetables. This finding supports previous reports on thermal insulation materials that reduced mass loss in amaranth when covered with an insulated pallet cover of Reflectix™ composed of aluminum foil/0.8 cm polyethylene/bubble pack. They also found that insulated pallet cover (2%) reduced mass loss better than no cover (11%) during 6 h of display at a retail market [20].

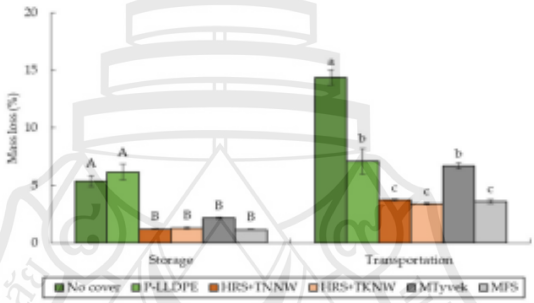

Figure 11. Mass loss (%) among the six treatments after simulated storage at 18 °C for 48 h and simulated transportation at 30 °C for 15 h. For Tukey's HSD post hoc test, different letters in each simulation test indicate significant differences at $p < 0.05$. Values are mean ±S.E. from five replicates.

3.5. Incidence of Decay

MTyvek treatment exhibited the lowest percent of no decay (84.0%) compared with MFS (90.8%), HRS + TKNW (93.6%), no cover (95.9%), P-LLDPE (96.5%) and HRS + TNNW (99.1%) (Figure 12). The HRS + TNNW treatment exhibited the best thermal insulation performance to prevent postharvest loss of okra from decay (lowest decay incidence with 0.9%) and was found better than HRS + TKNW (higher decay incidence with 6.4%) (Figure 13). There are several possible explanations for this result. Firstly, thin nonwoven (TNNW) and perforated HRS combined with partial bonding, providing air space between the two layers. The TNNW material absorbed moisture from transpiration and respiration processes. Secondly, the moisture inside the cover passed through the nonwoven (inner layer) to the air space between the layers and provided an area for collecting moisture. From our observations, after the simulated transportation, HRS + TKNW, MTyvek and MFS exhibited moisture condensation on the inner side of the cover and this yielding a higher rate of decay, compared to HRS + TNNW. Low WVP level of MTyvek and MFS (Table 2) reduced moisture vapor transfer to the outside, thus leading to high decay. Observation on decay of okra in this study was consistent with Rattanakaran et al. [16], which reported the lowest percentage of okra decay (<20%) in treatments of room cooling combined with HRS + TNNW and MFS, compared to that in P-LLDPE (50%). The results implied that room cooling for okra was important before covering, and significantly reduced okra

decay. This result concurred with Emond and Germain [48] who reported that pallets covered with metalized bubble wrap had high condensation on the cases that led to rapid decay and increased mold growth in 'Kent' mango. From our findings, the application of thermal insulation covers was suggested for short periods of okra transportation under high temperature to reduce decay and heat accumulation. Gas treatment may reduce decay and control insects by active modified atmosphere packaging inside thermal insulation covers. In strawberry, flushing CO_2 gas (10–16%) within the pallet cover was applied to reduce decay during truck transportation. Tectrol pallets treated with a partial vacuum and flushing CO_2 exhibited significantly less decay (36%) compared to the noncovered control (41%) [49]. Phosphine fumigation was also applied in thermal insulation covers to control western flower thrips in chilled lettuce [40].

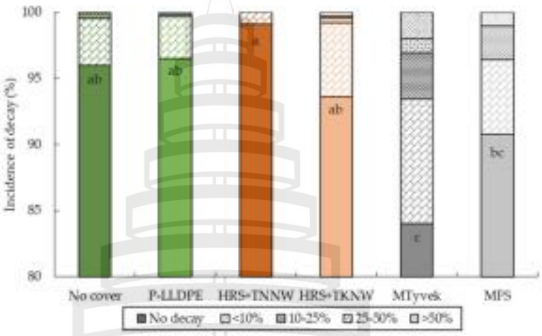

Figure 12. The percentage of decay incidence in six treatments after simulated storage at 18 °C for 48 h and simulated transportation at 30 °C for 15 h. No decay shown by different letters in each treatment indicates significant differences at $p < 0.05$ for Tukey's HSD post hoc test. Values are mean ± S.E. from five replicates.

Figure 13. Okra from six treatments after simulated storage at 18 °C for 48 h and simulated transportation at 30 °C for 15 h.

3.6. Pearson Correlation Analysis

In Table 4, material properties (thermal heat energy, R−value and WVP), temperature variables (rate of air and pulp temperature change at initial temperature (T_1) to 25 °C and 25 °C to 30 °C, accumulated time−temperature), okra quality (transpiration rate and vital heat during simulated storage and transportation, mass loss and decay incidence) were analyzed, using Pearson correlation, to present correlation coefficient value (r). Mass loss of okra showed positive correlation with thermal heat energy (Q_x) ($r = 0.702$) and transpiration rate (TR) during simulated storage ($r = 0.898$) and simulated transportation ($r = 0.995$), while mass loss of okra showed negative correlation with R−value ($r = -0.729$) and accumulated time−temperature (ATT) ($r = -0.939$). For the selection of thermal insulation materials, thermal heat energy (Q_x) ($r = 0.702$) and R−value ($r = -0.729$) properties were considered more than WVP to reduce mass loss in okra. Decay incidence of okra was related to WVP ($r = -0.682$), vital heat (VH) during transportation ($r = -0.744$) and rate of pulp temperature change during 25 °C to 30 °C ($r = -0.823$). The ATT throughout the simulated supply chain showed high correlation with both transpiration rate (TR) storage ($r = -0.770$) and TR transportation ($r = -0.922$) as well as mass loss ($r = 0.939$). Thus, the time-temperature variable affected transpiration as well as mass loss of okra throughout the supply chain. Results indicated that minimizing mass loss in okra could be achieved by focusing on thermal heat energy (Q_x) and R-value properties, which were identified as more significant factors than WVP. Minimizing decay incidence required attention on WVP, vital heat and rate of temperature change inside the covering.

3.7. Hierarchical Clustering Analysis

To compare the efficiency between the two thermal insulation cover prototypes and commercial covers, the overall performance of all treatment covers was analyzed by Hierarchical clustering analysis (HCA). Three main parameters; material properties (thermal heat energy, R-value and WVP), temperature variables (rate of air and pulp temperature change at the initial temperature (T_1) to 25 °C and 25 °C to 30 °C and accumulated time-temperature) and okra quality (transpiration rate, vital heat during simulated storage and transportation, mass loss and decay) obtained from the five cover treatments, were analyzed as shown in Figure 14. The dendrogram identified various groups of packaging covers. The first division as in-groups consisted of HRS + TNNW and HRS + TKNW with MFS, while the second and third groups consisted of MTyvek and P-LLDPE, respectively. Both developing prototypes of thermal insulation covers (HRS + TNNW and HRS + TKNW) exhibited material properties that affected temperature fluctuation and mass loss, similar to those of the commercial MFS cover. Interestingly, these prototypes (HRS + TNNW and HRS + TKNW) exhibited greater reduction of decay (approximately 8.3%) compared to MFS, while reducing mass loss (quantitative loss) to 2% and decay (quality loss) to 15.1% compared with the commercial MTyvek cover. Dieckmann et al. [50] studied the efficiency of nonwoven fabric as a base material for temperature-controlled deliveries. They found that air-laid nonwoven feather fiber showed potential for temperature control compared with the commercially available expanded polystyrene (EPS) packaging panel. In terms of environmental aspects and packaging sustainability, combined HRS and selected nonwoven material should be developed as a thermal insulation prototype for cover application to reduce foam material (MFS), with lower postharvest loss (decay 1%) for distribution packaging.

Table 4. Pearson correlation analysis evaluating by material properties, transpiration rate, vital heat, air and pulp temperatures and okra quality.

	Qx	WVP	R Value	TR_ Storage	TR_ Transport	VH_ Storage	VH_ Transport	RoP T1to25	RoP T25to30	RoA T1to25	RoA T25to30	ATT	ML	Decay
Qx	1.000													
WVP	0.674 **	1.000												
R_value	−0.925 **	−0.791 **	1.000											
TR_ storage	0.743 **	0.723 **	−0.874 **	1.000										
TR_ transport	0.679 **	0.549 *	−0.720 **	0.911 **	1.000									
VH_ storage	−0.361	−0.407	0.408	−0.283	−0.175	1.000								
VH_ transport	0.205	0.406	−0.441	0.203	−0.089	−0.102	1.000							
RoP T1to25	0.659 **	0.849 **	−0.851 **	0.819 **	0.625 *	−0.278	0.578 *	1.000						
RoP T25to30	0.287	0.519 *	−0.503	0.340	−0.046	−0.214	0.781 **	0.651 **	1.000					
RoA T1to25	0.743 **	0.745 **	−0.816 **	0.692 **	0.543 *	−0.524 *	0.343	0.647 **	0.364	1.000				
RoA T25to30	0.514 *	0.695 **	−0.760 **	0.712 **	0.518 *	−0.402	0.721 **	0.854 **	0.624 *	0.635 *	1.000			
ATT	−0.655 **	−0.310	0.605 *	−0.770 **	−0.922 **	0.104	0.284	−0.414	0.210	−0.416	−0.294	1.000		
ML	0.702 **	0.537 *	−0.729 **	0.898 **	0.995 **	−0.164	−0.088	0.633 *	−0.052	0.532 *	0.506	−0.939 **	1.000	
Decay	−0.271	−0.682 **	0.449	−0.216	0.128	0.289	−0.744 **	−0.622 *	−0.823 **	−0.488	−0.525 *	−0.365	0.132	1.000

Note: Rate of pulp temperature changes (RoP); rate of air temperature changes (RoA); water vapor permeability (WVP); transpiration rate (TR); thermal heat energy (Qx); vital heat (VH); accumulated time-temperature (ATT); mass loss (ML). ** Correlation is significant at the 0.01 level (2-tailed). *Correlation is significant at the 0.05 level (2-tailed).

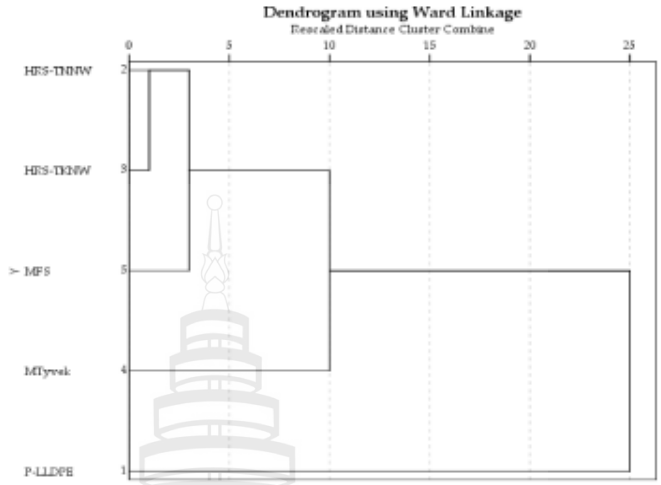

Figure 14. Hierarchical cluster analysis based on material properties, transpiration rate, vital heat, air and pulp temperatures and okra quality. Ward's method for dissimilarity was utilized during agglomerative hierarchical clustering.

4. Conclusions

The performance of thermal insulation covers on preserving quality of okra was evaluated. With MTyvek and MFS covers, the high moisture retention resulted in more condensation and greater decay (16.0% and 9.2%), while P-LLDPE (3.5%) and HRS + TNNW (0.9%) had lower levels than no cover (4.0%). Mass loss was significantly reduced by applying the HRS + TNNW, HRS + TKNW and MFS covers. Two thermal insulation prototypes; HRS combined with either TNNW or TKNW, showed good potential to maintain low temperature, reduce transpiration, and mass loss of okra compared to the two commercial thermal insulation materials (MTyvek and MFS) and typical plastic materials (no cover and P-LLDPE). Form results, it was suggested that thermal insulation covering for fresh okra should have material properties with low thermal heat energy (Q_x), high R-value and moderate WVP value to preserve cool temperature and delay okra senescence.

Author Contributions: J.R. conducted experiments, analyzed data, interpreted results, and assisted manuscript writing. R.S. co-investigated, interpreted results, and assisted data analysis. N.A. assisted data analysis. S.P. assisted material analysis. C.P. co-investigated, supported cover materials, interpreted results in material analysis, and assisted manuscript writing. H.K. provided comments and suggestions for the final draft of the manuscript. C.F.H.B. provided comments and suggestions for the final draft of the manuscript. S.C. was the principal investigator of the research, responsible for the overall research management, interpretation of results, and manuscript writing. All authors have read and agreed to the published version of the manuscript.

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References

1. Siemonsma, J.S. West African okra—Morphological and cytogenetical indications for the existence of a natural amphidiploid of *Abelmoschus esculentus* (L.) Moench and *A. manihot* (L.) Medikus. *Euphytica* **1982**, *31*, 241–252. [CrossRef]
2. Thai Customs. Statistic Report. 2020. Available online: http://www.customs.go.th/statistic_report.php?lang=en&tariff_code=07099990003 (accessed on 12 February 2021).
3. Tsado, E.K. Quality of postharvest handling of marketable okra fruits sold in Minna, Niger State, Nigeria. *Eur. J. Agric. For. Res.* **2015**, *3*, 33–45.
4. Perkins-Veazie, P. Commodity summaries: Okra. In *The Commercial Storage of Fruits, Vegetables and Florist and Nursery Stocks*; Gross, K.C., Wang, C.Y., Saltveit, M., Eds.; United States Department of Agriculture (USDA): Washington, DC, USA, 2016; pp. 430–432.
5. Finger, F.L.; Della-Justina, M.E.; Casali, V.W.D.; Puiatti, M. Temperature and modified atmosphere affect the quality of okra. *Sci. Agric.* **2008**, *65*, 360–364. [CrossRef]
6. Babarinde, G.O.; Fabunmi, O.A. Effects of packaging materials and storage temperature on quality of fresh okra (*Abelmoschus esculentus*) fruit. *Agric. Trop. Subtrop.* **2009**, *42*, 151–156.
7. Cheng, Z.; Gong, X.; Jing, W.; Peng, Z.; Li, J. Quality change of postharvest okra at different storage temperatures. *J. Food Eng. Technol.* **2018**, *7*, 43.
8. Huang, S.; Li, T.; Jiang, G.; Xie, W.; Chang, S.; Jiang, Y.; Duan, X. 1-Methylcyclopropene reduces chilling injury of harvested okra (*Hibiscus esculentus* L.) pods. *Sci. Hortic.* **2012**, *141*, 42–46. [CrossRef]
9. Greis, N.P. Management the "Cool Chain" A Cold Chain is Only as Cool as Its Warmest Link. Available online: https://www.asiacoldchainshow.com/uploads/Managing%20the%20Cool%20Chain.pdf (accessed on 21 February 2021).
10. Mercier, S.; Villeneuve, S.; Mondor, M.; Uysal, I. Time-temperature management along the food cold chain: A review of recent developments. *Compr. Rev. Food Sci. Food Saf.* **2017**, *16*, 647–667. [CrossRef]
11. Sargent, S.A.; Fox, A.J.; Coelho, E.C.M.; Locascio, S.J. Comparison of cooling and packaging methods to extend the postharvest life of okra. *Proceeding Fla. State Hortic. Soc.* **1996**, *109*, 285–290.
12. Rai, D.R.; Balasubramanian, S. Qualitative and textural changes in fresh okra pods (*Hibiscus esculentus* L.) under modified atmosphere packaging in perforated film packages. *Food Sci. Technol. Int.* **2009**, *15*, 131–138. [CrossRef]
13. Liu, J.; Yuan, Y.; Wu, Q.; Zhao, Y.; Jiang, Y.; John, A.; Yang, B. Analyses of quality and metabolites levels of okra during postharvest senescence by 1H-high resolution NMR. *Postharvest Biol. Technol.* **2017**, *132*, 171–178. [CrossRef]
14. FAO. *Good Practice in the Design Management and Operation of a Fresh Produce Packing-House*; FAO Region Office for Asia and the Pacific: Bangkok, Thailand, 2012; pp. 44–47.
15. Dhall, R.K.; Sharma, S.R.; Mahajan, B.V.C. Development of post-harvest protocol of okra for export marketing. *J. Food Sci. Technol.* **2014**, *51*, 1622–1625. [CrossRef]
16. Rattanakaran, J.; Saengrayap, R.; Prahsarn, C.; Kitazawa, H.; Chaiwong, S. Application of room cooling and thermal insulation materials to maintain quality of okra during storage and transportation. *Horticulturae* **2021**, *7*, 188. [CrossRef]
17. Burgess, G. Practical thermal resistance and ice requirement calculations for insulating packages. *Packag. Technol. Sci.* **1999**, *12*, 75–80. [CrossRef]
18. Singh, S.P.; Burgess, G.; Singh, J. Performance comparison of thermal insulated packaging boxes, bags and refrigerants for single-parcel shipments. *Packag. Technol. Sci.* **2008**, *21*, 25–35. [CrossRef]
19. Wang, G.; Zhao, J.; Wang, G.; Mark, L.H.; Park, C.B.; Zhao, G. Low-density and structure-tunable microcellular PMMA foams with improved thermal-insulation and compressive mechanical properties. *Eur. Polym. J.* **2017**, *95*, 382–393. [CrossRef]
20. Wheeler, L.; Kitinoja, L.; Barrett, D. Use of insulated covers over product crates to reduce losses in amaranth during shipping delays. *Agriculture* **2015**, *5*, 1204–1223. [CrossRef]
21. Sharp, A.K.; Irving, A.R. Insulating covers for pallets of food. In Proceedings of the I.I.F.-I.I.R. Commission D2, Prague, Czech Republic, 30 March–3 April 1981; pp. 139–148.
22. Melis, R.B. New Techniques and Methods for Cold Chain Monitoring and Tracking in Perishable Products. Ph.D. Thesis, Universidad Politécnica de Madrid, Madrid, Spain, 2016.
23. Chaiwong, S.; Bishop, C.F.H. Use of an insulated bag from the supermarket to maintain 'Elsanta' strawberry temperature to households. *Acta Hortic.* **2015**, *1079*, 187–192. [CrossRef]
24. Kitinoja, L. Use of Cold Chains for Reducing Food Losses in Developing Countries. Available online: http://www.postharvest.org/Cold_chains_PEF_White_Paper_13_03.pdf (accessed on 10 June 2020).
25. Harvey, B.V. Mild Chilling Injury of Banana (*Cavendish* cv. Williams) and Its Control in The Field. Ph.D. Thesis, The University of Adelaide, Adelaide, Australia, 2005.
26. ASTM. *Standard Test Methods for Water Vapor Transmission of Materials*; E96-E95; ASTM International: West Conshohocken, PA, USA, 1995; pp. 785–792.
27. ASTM. *Standard Test Method for Air Permeability of Textile Fabrics*; D737-96; ASTM International: West Conshohocken, PA, USA, 1996; pp. 230–234.

28. Saltviet, M.E. Measuring Respiration. Available online: http://ucce.ucdavis.edu/files/datastore/234-20.pdf (accessed on 10 June 2020).
29. Postharvest Research Laboratory. Laboratory manual for horticulture postharvest technology. In *Training Programe, 9th Horticulture Postharvest Technology*; Postharvest Research Laboratory, Kasetsart University: Nakhon Pathom, Thailand, 2004; pp. 24–27.
30. Kader, A.A.; Saltveit, M.E. Respiration and gas exchange. In *Postharvest Physiology and Pathology of Vegetables*, 2nd ed.; Bartz, J.A., Brecht, J.K., Eds.; Marcel Dekker Inc.: New York, NY, USA, 2003; pp. 7–29.
31. Patel, B.B.; Roy, F.S.; Saiyad, M.J.S.; Joshi, D.C. Respiration behaviour and heat of respiration of mango (cv. Langdo) under different storage conditions. *Int. J. Agric. Environ. Biotechnol.* **2016**, *9*, 855–859. [CrossRef]
32. Lufu, R.; Ambaw, A.; Opara, U.L. The contribution of transpiration and respiration processes in the mass loss of pomegranate fruit (cv. Wonderful). *Postharvest Biol. Technol.* **2019**, *157*, 110982. [CrossRef]
33. Iweka, C.; Uguru, H. Environmental factors on the physical characteristics and physiological maturity of okra (*Abelmoschus esculentus*, cv. Kirikou) pods and seeds. *Direct Res. J. Agric. Food Sci.* **2019**, *7*, 99–109.
34. Ngure, J.W.; Aguyoh, J.N.; Gaoquiong, L. Interactive effects of packaging and storage temperatures on the shelf-life of okra. *ARPN J. Agric. Biol. Sci.* **2009**, *4*, 43–52.
35. Harding, K.G. *Heat Transfer Introduction*; University of the Witwatersrand: Johannesburg, South Africa, 2018; pp. 1–62.
36. Mangaraj, S.; Goswami, T.K.; Panda, D.K. Modeling of gas transmission properties of polymeric films used for MA packaging of fruits. *J. Food Sci. Technol.* **2015**, *52*, 5456–5469. [CrossRef]
37. Manikantan, M.R.; Varadharaju, N. Preparation and properties of linear low density polyethylene based nanocomposite films for food packaging. *Indian J. Eng. Mater. Sci.* **2012**, *19*, 54–66.
38. Dutta, A. Redesigning the Coffee Laminate from Aluminum Foil Based Laminate to metalized Polyethylene Terephthalate Laminate: A Comparative Study. Ph.D. Thesis, Asian Institute of Technology, Bangkok, Thailand, 2015.
39. Dupont™, Tyvek®Cargo Covers: The Science behind the Covers. Available online: http://www.dupont.com/products-and-services/fabrics-fibersnonwovens/covers/articles/air-cargo-covers-science-behind.html (accessed on 10 November 2020).
40. Liu, Y.B. Low-temperature phosphine fumigation of chilled lettuce under insulated cover for postharvest control of western flower thrips, *Frankliniella occidentalis* (Pergande) (Thysanoptera: Thripidae). *J. Asia Pac. Entomol.* **2011**, *14*, 323–325. [CrossRef]
41. Gowen, A.A.; Tiwari, B.K.; Cullen, P.J.; McDonnell, K.; O'Donnell, C.P. Applications of thermal imaging in food quality and safety assessment. *Trends Food Sci. Technol.* **2010**, *21*, 190–200. [CrossRef]
42. Bycroft, B.L.; Brash, D.W.; Bollen, F. Using insulation and cooling to improve the asparagus cool chain. *Acta Hortic.* **1996**, *415*, 323–332. [CrossRef]
43. Li, Y.; Schrade, J.P.; Su, H.; Specchio, J.J. Transportation of perishable and refrigerated foods in Mylar foil bags and insulated containers: A time-temperature study. *J. Food Prot.* **2014**, *77*, 1317–1324. [CrossRef]
44. Dupont™, Tyvek®Air Cargo Covers Offer Ideal Protection for Your Perishable and Temperature-Sensitive Shipments. Available online: https://www.r-bag.hu/upload/files/DP-Tyvek-Air-cargo-cover-Brochure-K24389-2013.pdf (accessed on 11 June 2021).
45. Lim, B.S.; Lim, C.I.; Gross, K.C. High relative humidity under pallet coverage maintained 'Niitaka'pear fruit (*Pyrus pyrifolia* Nakai) quality during low temperature storage. *Korean J. Hortic. Sci. Technol.* **2005**, *23*, 135–139.
46. Xanthopoulos, G.T.; Templalexis, C.G.; Aleiferis, N.P.; Lentzou, D.I. The contribution of transpiration and respiration in water loss of perishable agricultural products: The case of pears. *Biosyst. Eng.* **2017**, *158*, 76–85. [CrossRef]
47. Rattanakaran, J.; Saengrayap, R.; Prahsarn, C.; Chaiwong, S. Model development and validation for mass loss attributes of okra under dynamic conditions. In Proceedings of the International Conference on Food and Applied Bioscience 2020, Chiang Mai, Thailand, 6–7 February 2020; pp. 134–139.
48. Emond, P.J.; Germain, M. Report: Study of Thermal Protection for Mango Pallets during Mixed Load Shipment, National Mango Board. Available online: https://www.mango.org/wp-content/uploads/2018/03/Thermal_Protection_for_Mango_Pallets_Eng-1.pdf (accessed on 9 May 2021).
49. Macnish, A.J.; Padda, M.S.; Pupin, F.; Tsouvaltzis, P.I.; Deltsidis, A.I.; Sims, C.A.; Brecht, J.K.; Mitcham, E.J. Comparison of pallet cover systems to maintain strawberry fruit quality during transport. *HortTechnology* **2012**, *22*, 493–501. [CrossRef]
50. Dieckmann, E.; Nagy, B.; Yiakoumetti, K.; Sheldrick, L.; Cheeseman, C. Thermal insulation packaging for cold-chain deliveries made from feathers. *Food Packag. Shelf Life* **2019**, *21*, 100360. [CrossRef]

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PUBLICATIONS

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Rattanakaran, J., Saengrayap, R., Prahsarn, C., Kitazawa, H., & Chaiwong, S. (2021). Application of room cooling and thermal insulation materials to maintain quality of okra during storage and transportation. *Horticulturae, 7*(7), 188.

Rattanakaran, J., Saengrayap, R., Prahsarn, C., & Chaiwong, S. (2020). *Model development and validation for mass loss attributes of okra under dynamic conditions*. In Proceedings of the International Conference on Food and Applied Bioscience on 6-7 February 2020 (pp. 134–139), Chiang Mai: Chiang Mai University.

Saengrayap, R., Rattanakaran, J., & Chaiwong, S. (2019). Application of artificial neural network for 'Cavendish' banana maturity and chilling injury prediction. *Acta Horticulturae, 1245*, 29-34.

Rattanakaran, J., Saengrayap, R., & Prahsarn, C. (2018). Application of nonwoven as a bunch cover for banana during winter season in Thailand. *Acta Horticulturae, 1210,* 35-42.

Saengrayap, R., Rattanakaran, J., & Chaiwong, S. (2018). Maturity prediction of banana with difference bunch cover materials using artificial neural networks. *Acta Horticulturae, 1210,* 213-220.

Kitazawa, H., Li, L., Hasegawa, N., Rattanakaran, J., & Saengrayap, R. (2018). Evaluation of shock-proof performance of new cushioning system for portable packaging of apples. *Environmental Control in Biology, 56*(4), 167-172.