

Influence of Water Vapor Permeability Differences in Pulp-molded Trays on the Quality of Stored Tomatoes

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Keywords. fruit vegetables, paraffin impregnation, mildew, storage, weight loss

Abstract. Preventing the occurrence of mildew and mold during the distribution of fresh produce is important. To reduce their occurrence, appropriate water vapor permeability is required for trays used as internal packaging. However, greater water vapor permeability may result in a poor appearance, such as wilting, as a result of significant weight loss from water loss. Thus, to evaluate the ability of pulp-molded trays to maintain the quality of fresh produce, we investigated the effect of differences in water vapor permeability of pulp-molded trays on mildew and mold occurrence, and weight loss in tomatoes, using paraffin-immersed and nonparaffin-immersed trays. The water vapor permeabilities of these materials were 27.0 and 362.3 g·m⁻²·d⁻¹, respectively. The results of two storage tests, conducted at 25°C and a maximum 78% relative humidity for 14 days, suggested that the use of the nonparaffin-immersed trays was effective in reducing the occurrence of mildew and mold. In contrast, although we recognized the possibility of weight loss of up to 4.8% when using this material, such water loss did not seem to affect the appearance of the tomatoes. These findings contribute to the optimal design of water vapor permeability of pulp-molded trays and plastic trays used for the same purpose.

Tomatoes (*Solanum lycopersicum*) are among the most important vegetables in the world (Slimestad and Verheul 2009) because of their wide industrial use and consumption in their raw form. In Japan, tomatoes are recognized as a vital vegetable for the agricultural and food industries, and are specified as one of the vegetables designated by the Ministry of Agriculture, Forestry and Fisheries (2025). Moreover, functional substances such as lycopene and rutin, which are present in tomatoes (Carvalho et al. 2021; Slimestad et al. 2008; Tan et al. 2021), might be attractive and are expected to expand their use from the viewpoint of physiological regulatory functions in humans.

However, because mature tomatoes are perishable, the occurrence of bruises caused by

mechanical stress such as shock and vibration during distribution is a concern (Pathare and Al-Dairi 2021; Sophea et al. 2024). Because tomatoes are climacteric fruits (Kou et al. 2021; Quinet et al. 2019), they are often harvested at an immature stage and then allowed to ripen gradually during distribution. However, there is concern about the occurrence of mildew and/or mold on the tomatoes (Ahmed et al. 2016), because the duration from harvest to sale increases in such a situation.

Vegetables, including tomatoes, continue to respire after they are harvested. Transpiration, resulting from respiration and evaporation from the surface during distribution, causes a decrease in water content in vegetables. In addition, temperature fluctuations during distribution lead to

condensation on the surface of fresh produce (Bovi et al. 2019) and increase the risk of bacterial deterioration (Linke and Geyer 2013; Linke et al. 2021). The occurrence of mildew and/or mold spoils the commercial quality of the tomatoes, even if it occurs on inedible parts, such as the calyx (Takahashi et al. 2019).

Plastic or paper-based trays are often used to distribute tomatoes (Dladla and Workneh 2023). In a comparison between the two materials, the former generally has less water vapor permeability, which might enhance the mildew and/or mold occurrence as a result of condensation around the tomatoes (Linke and Geyer 2013; Shrivastava et al. 2023). However, the latter has greater water vapor permeability, which might accelerate wilting caused by a decrease in water from the fruit. In fact, corrugated fiberboard boxes with greater water vapor permeability accelerated the decrease of water in leafy vegetables during storage (Wambraw et al. 2020a, 2020b). For tomato distribution, both pulp-molded and plastic-based trays, which have a shape similar to the former, are used, as with other fruit (Batt et al. 2019; Berardinelli et al. 2005). However, few studies have compared the performance of both trays in terms of tomato quality during storage.

We investigated the effects of differences in water vapor permeability of tomato trays on the occurrence of mildew and/or mold and weight loss resulting from water loss during storage. We used pulp-molded trays with or without paraffin impregnation to determine whether the condition in which only water vapor permeability was different. A paraffin-impregnated tray was assumed to be a high water-barrier tray, such as plastic. As another important quality item for tomatoes (Cai et al. 2024; Kader 2008), we compared the soluble solids content (measured in degrees Brix) of the tomatoes before and after the storage test.

Materials and Methods

An overview of the procedure used in this study is shown in Supplemental Fig. 1.

Evaluation of water vapor permeability of pulp-molded tray (Expt. 1)

Thus far, it has been difficult to evaluate the water vapor permeability of spherical materials, although several methods have been proposed for seat-like materials. In this study, we propose a new method for this purpose. A pulp-molded tray with 24 holes (Nippon Molding, Anjou, Japan) was used in this experiment. The dimensions were 0.293 × 0.430 × 0.023 m. Ten spherical domes were cut from each hole in the tray (dome surface area, ~0.0057 m²). Then, we immersed five domes into melted paraffin (pellet-type paraffin wax; e-berry, Osaka, Japan) in a hot-water bath [paraffin-impregnated trays (PIT)]. We hypothesized that the water vapor permeability of this tray would be similar to that of a plastic tray. The remaining five domes were not immersed in the melted paraffin [nonparaffin-impregnated trays (N-PIT)]. We prepared a polyethylene

terephthalate cup (HM-15; Shinwa, Nara, Japan) containing ~65 mL tap water. The cup dimensions were as follows: top, 70 mm; bottom, 46 mm; and height, 90 mm. Last, the opening of the cup was covered with the dome of the PIT or N-PIT, as shown in Fig. 1. To seal and fill the gap between the dome and the edge of the cup, we rolled a piece of plastic tape around it.

The PIT and N-PIT cups were placed in a constant-temperature chamber (IN604; Yamato Scientific, Tokyo, Japan). The chamber temperature was set to 10 °C, and the relative humidity was less than 50% to accelerate the evaporation through the trays. We measured the weight (in grams) of the cups with the tray at 0, 4, 6, and 17 d after the start. Thus, the weight loss (measured in grams) was assumed to be a result of the evaporation of water through the PIT and N-PIT domes. Under these conditions, a decrease in water flowing through the cup was considered. Therefore, as a blank, we prepared the same cup with ~65 mL tap water covered with aluminum foil. The weight loss (measured as a percentage) of each cup was calculated by using a digital balance (GX-4000; A&D, Tokyo, Japan) and the following equation:

$$\text{Weight loss (\%)} = \left[\left(1 - \frac{a}{b} \right) - \left(1 - \frac{c}{d} \right) \right] \times 100,$$

where a , b , c , and d are the weight of the cup each day, the initial weight of the cup (on day 0), the weight of the blank each day, and the initial weight of the blank (on day 0), respectively. From the value of weight loss in the cup, we also calculated the weight loss rate (measured as a percentage) and water vapor permeability (measured in grams per square meter per day) of the PITs and N-PITs.

Evaluation of mildew and mold occurrence, weight loss, and soluble solids content of tomatoes (Expt. 2)

Preparation of molded tray. A pulp-molded tray with 24 holes (Nippon Molding) was

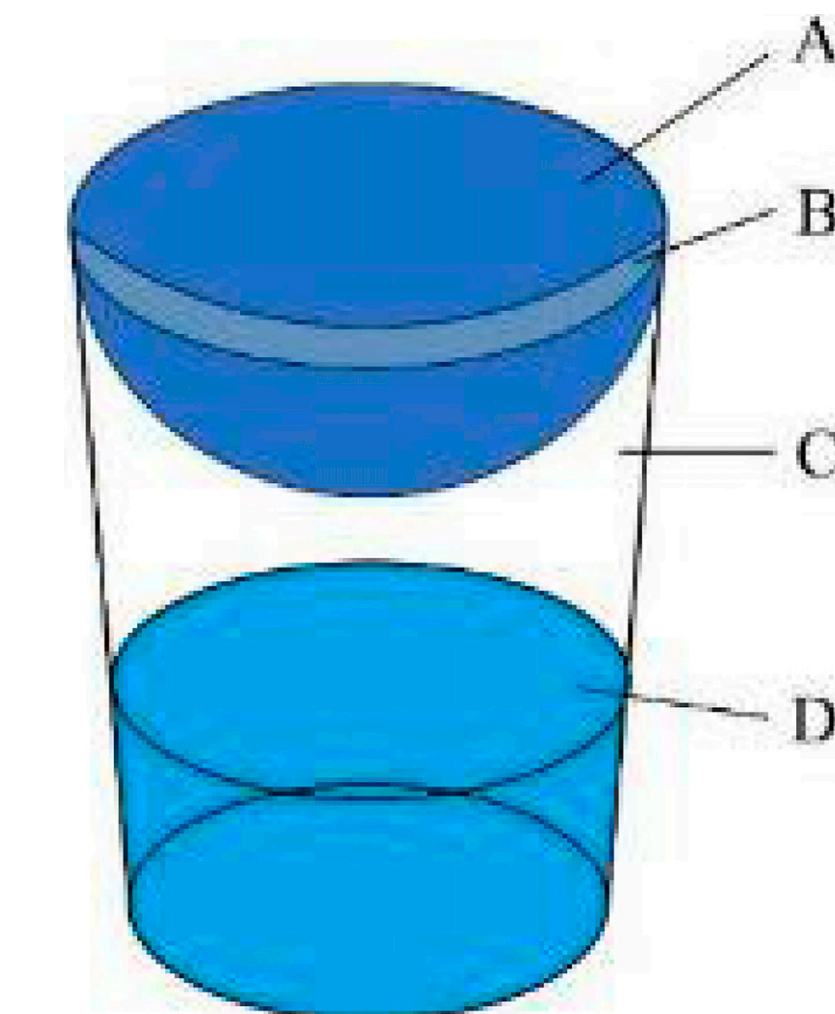


Fig. 1. Setup to evaluate the water permeability of pulp-molded trays. (A) Paraffin-impregnated and nonparaffin-impregnated trays (dome). (B) Plastic tape to seal and fill the gap between the dome and cup. (C) Polyethylene terephthalate-made cup. (D) Tap water (~65 mL).

used in this experiment. The dimensions were $0.280 \times 0.417 \times 0.017$ m, and the diameter of each hole was 0.07 m. The tray was cut to dimensions of 0.255×0.195 m,

with six holes (Fig. 2). Eight cutout trays were prepared. Paraffin, the same type used in Expt. 1, was placed in a metal vat, and the vat was placed in a natural convection dryer

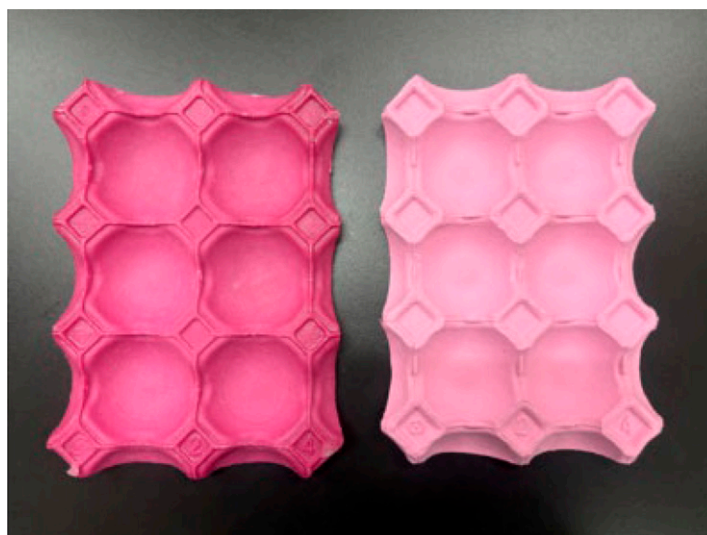


Fig. 2. Appearance of paraffin-impregnated tray (left) and nonparaffin-impregnated tray (right).

Received for publication 9 Sep 2025. Accepted for publication 25 Oct 2025.

Published online 18 Nov 2025.

We are grateful for the support provided by Nippon Molding Co Ltd (Anjou, Japan).

This study was funded, and material support was provided by, Nippon Molding Co Ltd.

Data obtained during the study are available from H.K. upon request.

The authors declare they have no conflict of interest. M.O. and Y.U. contributed equally to this work.

H.K. contributed to conceptualization; M.O., Y.U., and H.K. contributed to the methodology;

M.O., Y.U., and H.K. contributed to the formal analysis and investigation; M.O., Y.U., T.N., and H.K. contributed to writing the original draft;

R.S. S.C., and T.N. reviewed and edited the manuscript; and H.K. participated in funding and resource acquisition, and provided supervision.

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Received for publication 9 Sep 2025. Accepted for publication 25 Oct 2025. Published online 18 Nov 2025.

Table 1. The average weight, longitudinal and lateral diameters, and degree of maturity ($\pm$ standard deviation) of the tomatoes in the storage test.

Trial	Weight (g)	Diam (mm)		Degree of fruit maturity ⁱ
		Longitudinal	Lateral	
First	158.0 $\pm$ 9.7 ⁱⁱ	56.3 $\pm$ 2.2 ⁱⁱⁱ	64.8 $\pm$ 2.8 ⁱⁱⁱ	5.5
Second	171.8 $\pm$ 15.0*** ⁱⁱⁱ	56.4 $\pm$ 0.3NS ^{iv}	69.8 $\pm$ 0.1* ^{iv}	5.3NS

ⁱ green = 1 point, breaker = 2 points, turning = 3 points, pink = 4 points, light red = 5 points, and red = 6 points.

ⁱⁱ n = 24.

ⁱⁱⁱ n = 4.

^{iv} n = 5.

NS, *, *** Nonsignificant or significant at the 0.1% or 5% levels by Welch's *t* test.

(ONW-300SB; As-one, Osaka, Japan). We immersed four of the eight trays in melted paraffin for 8 min (4 min from the top surface and 4 min from the bottom surface) (Fig. 2). The weight of the impregnated paraffin in each tray was $\sim$ 37 g. Then, PITs-Expt. 2 (PIT-2s) and N-PIT-2s were prepared. In this experiment, we hypothesized that the water

vapor permeability of the PIT-2s would be similar to that of a plastic tray.

Storage test for tomatoes. The storage test for tomatoes was performed twice. The first trial, conducted 15 Sep 2024, used tomatoes produced in Hokkaido Prefecture, Japan. The second trial, conducted Nov 5 2024, used tomatoes produced in Kumamoto Prefecture,

Japan. For both trials, we selected 24 tomatoes, without any defects such as decay or bruising, from a total of 40 tomatoes. The average weight, longitudinal and lateral diameters, and degree of maturity of the tomatoes are listed in Table 1. The degree of tomato maturity was assessed via visual inspection based on a color chart for tomato producers (United Fresh Fruit & Vegetable Association 1975). The tomato ripening stage was scored by ripening and color from green to full red, where green = 1 point, breaker = 2 points, turning = 3 points, pink = 4 points, light red = 5 points, and red = 6 points.

Twelve tomatoes were used in the N-PIT-2s and PIT-2s. We prepared two trays and used six tomatoes per tray in each trial. To follow the conventional approach used in Japan, tomatoes placed on the trays upside down were set in a corrugated fiberboard box designated for tomato distribution (BF-C5 $\times$ C5; Aipakku, Sabae, Japan; internal size, 0.255 $\times$ 0.097 m). Each fiberboard box containing tomatoes was placed in a constant-temperature chamber (IN804; Yamato Scientific). The layout of each box used during the experiment is shown in Fig. 3. The location of each box with tomatoes was shuffled according to the measurement of weight and observation of the appearance of tomatoes, as noted later.

To induce condensation on tomatoes, first, the temperature of the chamber was set to 10°C for 2 d. At that time, the relative humidity inside the chamber was less than 50%. Next, the boxes containing the tomatoes were enveloped in a 45-L, 0.03-mm-thick low-density polyethylene bag and placed in the chamber. We then changed the temperature of the chamber to 25°C for 2 weeks. Under these conditions, the relative humidity inside the bag was finally raised to 78%. The temperature and final humidity were similar to the average values from June to August in Tokyo, Japan.

To evaluate the quality of tomatoes during the experiment, we removed tomatoes at 0, 4, 10, and 14 d after changing the temperature, and determined their weight using the previously mentioned digital balance and the following equation:

$$\text{Weight loss (\%)} = \left(1 - \frac{a}{b}\right) \times 100,$$

where *a* and *b* show the weight of the tomatoes each day and the initial weight of the tomatoes, respectively. We also observed whether mildew and/or mold occurred on the calyx on day 4 (Fig. 4). In addition, we measured the soluble solids content at 0 and 14 d after starting, using a refractometer (HI96801; Hanna Instruments, Cluj-Napoca, Romania).

Statistical analysis

For the weight loss of the cup with water in Expt. 1 and the tomatoes Expt. 2, we used Welch's *t* test to compare data within the same measurement period. In addition, Fisher's exact test was used to compare the number of tomatoes with mildew and mold present on the

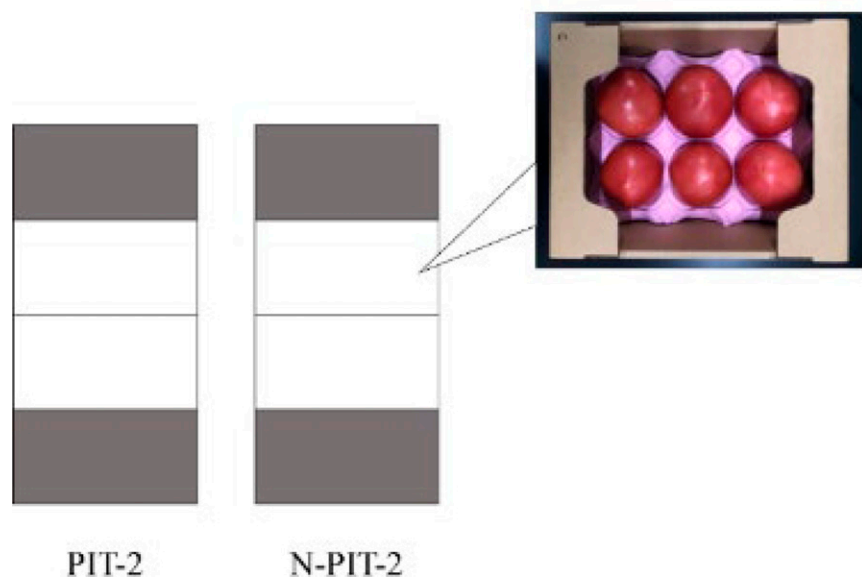


Fig. 3. Set up of corrugated boxes containing tomatoes. White boxes indicate boxes containing the fruit sample; dark-gray boxes reflect empty boxes for balance. N-PIT-2 = nonparaffin-impregnated tray Expt. 2; PIT-2 = paraffin-impregnated tray Expt. 2.

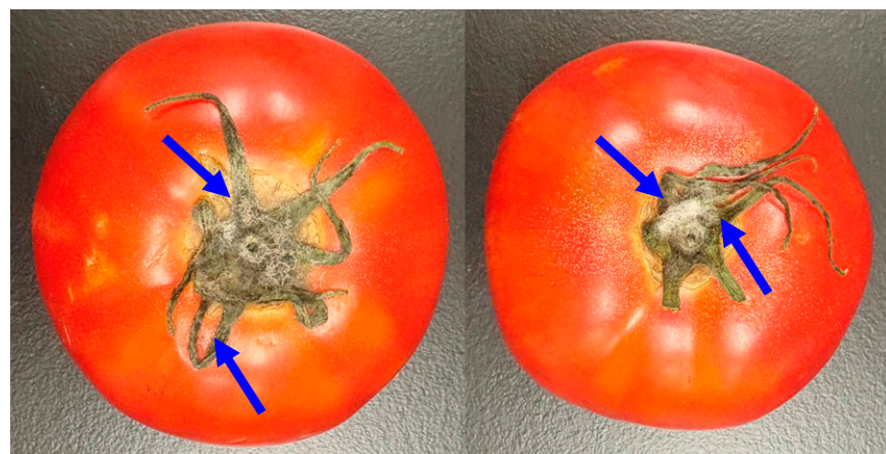


Fig. 4. Examples of mildew (flocculent area) and mold (black spot) on the calyx.

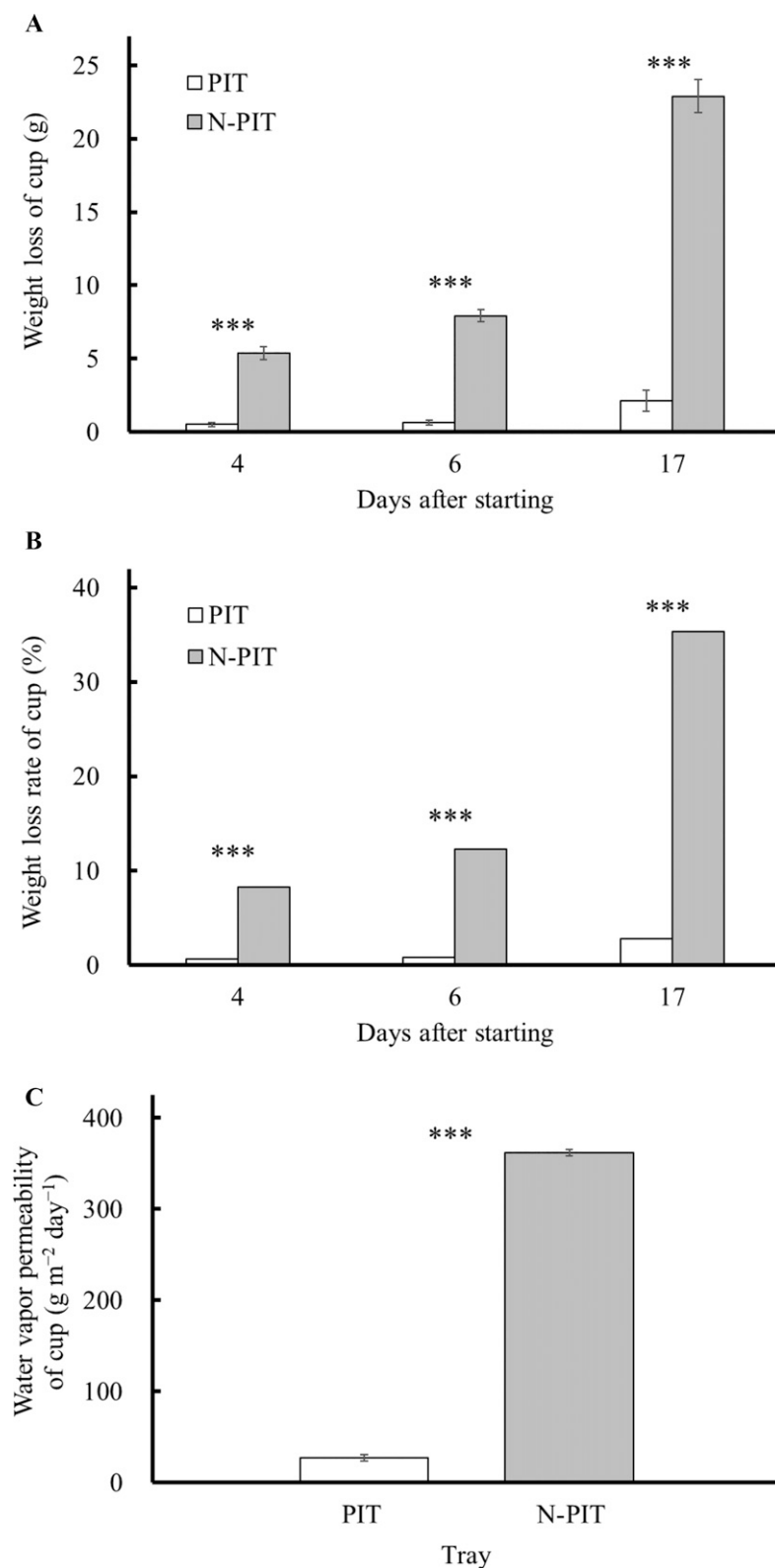


Fig. 5. Change in weight loss (A) and its rate (B) in the plastic cup containing water, and water vapor permeability of pulp-molded trays (C). The error bars in panels (A) and (C) show the standard deviation ($n = 5$ and 3 , respectively). N-PIT = nonparaffin-impregnated tray; PIT = paraffin-impregnated tray. *** Significant difference according to Welch's t test ($P < 0.001$).

calyxes. For both tests, a spreadsheet program (Excel 2021 v. 2411; Microsoft Japan, Tokyo, Japan) with add-in software (BellCurve; Social Survey Research Information, Tokyo, Japan) was used.

Regarding the first and second trials of Expt. 2, 12 tomatoes were divided and packed into two corrugated fiberboard boxes (6×2). However, if there were no significant differences in the weight loss of the tomatoes

Table 2. Effect of paraffin impregnation on pulp-molded trays in terms of mildew and mold on the calyx on day 4.

Trial	Type of tray	n	Rate (%)
First	Paraffin-impregnated	10	83
First	Nonparaffin-impregnated	3*	25
Second	Paraffin-impregnated	10	83
Second	Nonparaffin-impregnated	4*	33

* Significant at $P < 0.05$ (Fisher's exact test, $n = 12$).

between the two boxes with each tray type, we carried out the previously mentioned statistical analyses as $n = 12$. At that time, we used Welch's t test to confirm these findings.

Results

Evaluation of water vapor permeability of pulp-molded tray (Expt. 1)

The weight loss in the PIT cups on days 4, 6, and 17 was 0.5, 0.6, and 2.1 g, respectively (Fig. 5A). Compared with day 0, the weight loss rates were 0.7%, 0.8%, and 2.8%, respectively (Fig. 5B). In contrast, the weight loss in N-PIT-2 cups on the same day were 5.4, 7.9, and 22.9 g, respectively. Compared with day 0, the weight loss on days 4, 6, and 17 was 8.3%, 12.3%, and 35.4%, respectively, with significant differences between both treatments at all measurement periods ($P < 0.001$). The weight loss rates per day for PIT-2s and N-PIT-2s at each measurement period were calculated as 0.2%, 0.1%, and 0.2%; and 2.1%, 2.0%, and 2.1%, respectively. Therefore, for both treatments, it was confirmed that weight loss per day was almost constant. When the water vapor permeability of both treatments was calculated based on the average values of three measurement periods, the values were 27.0 and 362.3 $\text{g m}^{-2} \text{ d}^{-1}$, respectively. A significant difference ($P < 0.001$) was found between the two trays (Fig. 5C).

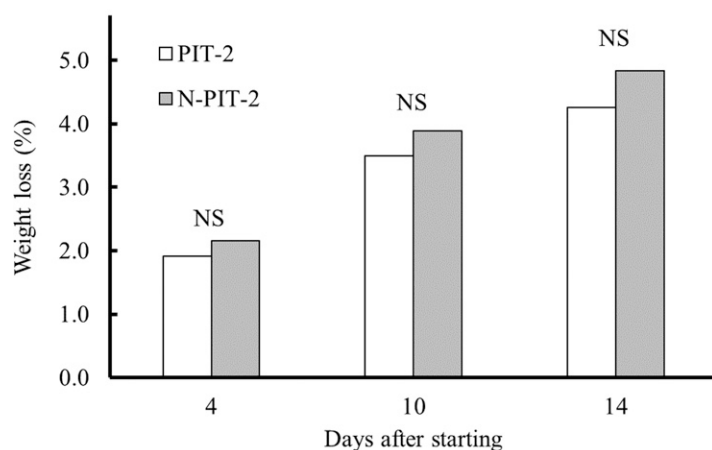
Evaluation of mildew and mold occurrence, weight loss, and soluble solids content of tomatoes (Expt. 2)

Mildew and mold occurrence. In both trials, there were no significant differences among the investigated tomatoes when stored in boxes of the two tray types. For the first trial, the occurrence of mildew and mold on the calyx was observed in both treatments on day 4. However, for the PIT-2s, the number of tomatoes with these symptoms was greater than those in N-PIT-2s (Table 2), and a significant difference was observed in the rate between the two treatments ($P < 0.05$). In the second trial, a similar tendency was observed for the occurrence of mildew and mold on the calyx as in the first trial. For PIT-2s, the number of tomatoes with mildew and mold on day 4 was greater than that for N-PIT-2s (Table 2), and a significant difference was observed in the rate between the two trays. In addition, the occurrence of mildew and mold remained unchanged throughout the storage period (Fig. 6).



Fig. 6. Appearance of tomatoes on day 14 in the second trial. (Top row) Fruit from paraffin-impregnated tray. (Bottom row) Fruit from nonparaffin-impregnated tray.

A First trial



B Second trial

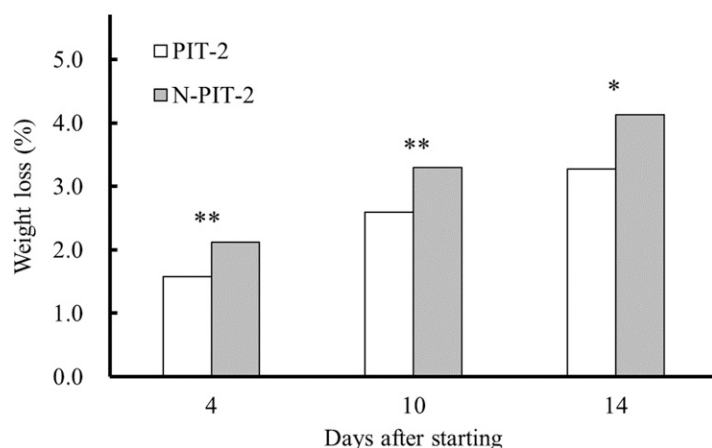


Fig. 7. Effect of paraffin impregnation on pulp-molded trays on the weight loss of tomato fruit for the first (A) and second (B) trials. N-PIT-2 = nonparaffin-impregnated tray Expt. 2; PIT-2 = paraffin-impregnated tray Expt. 2. NS, *, ** Nonsignificant according to the Welch's *t* test ($P < 0.05$, $n = 12$), or significant at the 1% or 5% levels using Welch's *t* test ($n = 12$), respectively.

Weight loss. In both trials, the weight loss of the tomatoes decreased gradually, corresponding to the extension of storage time (Fig. 7A and 7B). For the first trial, the changes in weight loss on days 4, 10, and 14 in the PIT-2 group were 1.9%, 3.5%, and 4.3%, respectively (Fig. 7A). The values for N-PIT-2s were 2.2%, 3.9%, and 4.8%, respectively, and no significant differences were observed between the treatments in any of the measurement periods. For the second trial, the PIT-2 values on days 4, 10, and 14 were 1.6%, 2.6%, and 3.3%, respectively (Fig. 7B). The values for N-PIT-2s on the same days were 2.1%, 3.3%, and 4.1%, respectively, and significant differences were observed between both treatments in all measurement periods ($P < 0.01$ or 0.05).

Soluble solids content. No significant difference was observed in soluble solids content between the two treatments on day 14 in the first trial (Table 3). A similar tendency was shown in the second trial, and the result was consistent with that of the first trial.

Discussion

The results of Expt. 1 shown in Fig. 5 demonstrate that paraffin impregnation of the molded tray reduced its water vapor permeability. Therefore, the enhanced occurrence of mildew and mold on the calyx in Expt. 2 (Table 2) was induced by excess moisture around the tomatoes, including the calyx covered with the PIT-2s. It is known that the range of water vapor permeability of plastics such as polypropylene and low-density polyethylene used as packaging materials for fresh produce (including tomatoes) is ~ 5 to $20 \text{ g} \cdot \text{m}^{-2} \cdot \text{d}^{-1}$ (Sanyo-Gravure 2018). Thus, our results also suggest that the use of plastic trays might increase the occurrence of mildew and/or mold on tomatoes during transportation, in addition to the necessity of a design for plastic trays to control the occurrence of condensation (Geyer et al. 2015; Rux et al. 2016). Conversely, the decrease in the occurrence of mildew and mold in N-PIT-2s was attributed to a decrease in humidity around the tomatoes, including the calyx, as a result of the greater water vapor permeability of the molded tray.

The results of the second trial in Expt. 2 indicate that greater water vapor permeability of trays is a cause of significant weight loss in tomatoes. It is suggested that such a decrease was caused by transpiration resulting from respiration or evaporation from the calyx (Takahashi et al. 2019) as well as from the fruit surface. Thus, the decrease in the weight loss of N-PIT-2s in the second trial was induced by the greater water vapor permeability of the molded tray. Respiration, which is related to transpiration in tomatoes, a typical climacteric fruit, is greater at the breaker stage than at the red-ripe stage (Bapary et al. 2024; Chrysargyris et al. 2021). The degree of maturity of the tomatoes used in the first trial was 5.5 points,

Table 3. Effect of paraffin impregnation on pulp-molded tray with regard to soluble solids contents of tomatoes.

Trial	Type of tray	Day 0 (°Brix)	Day 14 (°Brix)
First	Paraffin-impregnated	4.2 (n = 5)	4.1 (n = 4)
First	Nonparaffin-impregnated	4.2 (n = 5)	4.2 (n = 4)NS
Second	Paraffin-impregnated	4.4 (n = 5)	3.9 (n = 4)
Second	Nonparaffin-impregnated	4.4 (n = 5)	4.0 (n = 4)NS

NS Nonsignificant using Welch's *t* test.

and that of the second trial was 5.3 points. No significant difference was observed between the two trials (Table 1). However, significant differences were observed in the initial weight and width of the tomatoes between the two trials. Therefore, differences in the surface area of tomatoes result in differences in the degree of weight loss. In any case, the maximum weight loss in the N-PIT-2s was 4.1%, which did not exceed 5.0%—a criterion for the loss of commercial value in Japan (Shiina 2003). As far as we observed the appearance of tomatoes, this weight loss did not affect the commercial quality of the main body of the fruit (Fig. 6). Moreover, countermeasures have been proposed for tomatoes to reduce weight loss during storage (Buthane et al. 2025; Buthelezi 2025).

Soluble solids content is an important factor in determining the taste of fresh produce, including tomatoes (Cai et al. 2024; Kader 2008). However, several reports on quality changes in strawberries, tomatoes, and cabbage during storage have suggested that little or no change in soluble solid content is typically observed (Kabir et al. 2020; Kitazawa et al. 2013; Wambrauw et al. 2020a, 2020b). Therefore, in both trials, no significant differences in soluble solids content occurred when different trays were used.

Conclusion

The results of our study demonstrate that appropriate water vapor permeability is required for trays used for tomato distribution to reduce the risk of mildew and mold occurrence while maintaining negligible water loss, at least during storage for ~2 weeks. However, our future work will focus on tray designs that reduce both mildew and mold occurrence as well as minimize water loss. We believe our findings will contribute to the optimization of water vapor permeability in plastic trays used for the same purpose as paper trays, including pulp-molded trays, and will expand the options available to packaging designers or supply chain managers.

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