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Thermal and Energy Performance of a Modular-Airflow Air Fryer for Dehydration And Thawing**Jolanda Ch. E. Lamaega¹, Tommy B. Ogie², Frangky J. Paat², Sanriomi Sintaro^{3*}**¹Food Technology Study Program, Faculty of Agriculture, Universitas Sam Ratulangi, Manado, Indonesia²Agrotechnology Study Program, Faculty of Agriculture, Universitas Sam Ratulangi, Manado, Indonesia³Information Systems Study Program, Faculty of Mathematics and Natural Sciences, Universitas Sam Ratulangi, Manado, Indonesia*Corresponding author:
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Abstract. Affordable postharvest processing equipment requires careful management of heat and airflow, particularly when electrical capacity is limited. This study assessed the thermal and energy performance of a compact modular-airflow food-processing chamber and examined its application to fruit dehydration and frozen-meat thawing. A 15.6 L insulated chamber used incandescent heaters rated at 60, 100, and 150 W and interchangeable recirculation, exhaust, and ambient-air intake modules. The no-load thermal experiment followed a $3 \times 2 \times 2$ factorial arrangement of heating power, airflow mode (recirculation or exhaust), and one or two active fan modules, with three replicates per condition. Temperature, stabilization time, and 15-min electrical consumption were evaluated; fruit dehydration and meat thawing were reported descriptively. Recirculation maintained higher chamber temperatures than exhaust operation. Using two recirculation modules reduced the reported apparent vertical temperature difference by approximately 53–62% compared with one module. Electrical use during the no-load tests ranged from 15.53 to 38.57 Wh. In the fruit trials, the 150 W two-module exhaust treatment produced the highest recorded gravimetric mass losses, 69.0% for citrus and 67.6% for strawberry, with specific energy consumption of 2.29 and 2.34 Wh per gram of removed mass, respectively. Two-module ambient-air intake shortened the observed thawing endpoint at 60 and 100 W. These findings indicate that interchangeable airflow arrangements can support distinct thermal-processing tasks within one small chamber, although further product-quality and airflow measurements are needed before broader performance claims can be made.

Keywords: air circulation; dehydration; energy consumption; food-processing technology; thawing.

INTRODUCTION

Postharvest processing of agricultural commodities depends on practical technologies that can control heat and moisture while maintaining manageable energy requirements. Dehydration is particularly relevant to fruit and vegetable handling because the removal of water can facilitate further processing and storage, although product quality depends on the processing conditions. Reviews of agricultural-product drying describe energy demand and treatment severity as important

considerations for technology selection (Skåra et al., 2023; Martynenko & Vieira, 2023; AlZohbi et al., 2026). Experimental work on corn kernels has also shown that airflow recirculation can be incorporated into a crop-drying system (Suherman et al., 2025).

Thermal processing involves coupled heat transfer, product geometry, processing duration, and air movement. Studies of hot-air frying and convection cooking have demonstrated that these variables are relevant to moisture removal and product characteristics (Téllez-

Morales *et al.*, 2024; Aliberti *et al.*, 2025). Infrared-assisted food drying likewise depends on the interaction between the heating source and the material being processed (Delfiya *et al.*, 2022; Deepika & Sutar, 2024). For small, low-power chambers, the available heater output may be constrained, increasing the practical importance of air distribution rather than simply increasing nominal power.

Airflow distribution is an important design consideration in compact dryers. Sabat *et al.* (2021) evaluated an air disperser to improve the spatial consistency of drying conditions, whereas El-Mesery *et al.* (2023) examined airflow-distribution arrangements in convection dryers. Meng *et al.* (2022) further reported that a modified air-side transport approach can affect fruit and vegetable drying performance. These studies provide a basis for examining airflow arrangement as a controllable feature in smaller processing chambers, while recognizing that direct air-velocity measurement is needed to characterize flow intensity quantitatively.

Air recirculation and exhaust provide different thermal and mass-transfer functions. Recirculation can reduce the loss of warm air from the processing space, while exhaust is intended to remove moisture-laden air. Closed-loop drying systems have been examined for their thermal and energy characteristics (Hamid *et al.*, 2022; Tunçkal *et al.*, 2022). Nevertheless, higher chamber temperature alone is not a sufficient indicator of dehydration performance: the mass removed and the associated energy input must be considered together (Martynenko & Vieira, 2023; AlZohbi *et al.*, 2026).

Thawing of frozen animal products presents a different processing objective. A shorter thawing period may be desirable, but temperature heterogeneity, mass loss, and surface changes also matter. Previous studies have compared air-thawing arrangements and alternative

thawing techniques in relation to the quality of meat products (Lee *et al.*, 2021; Gan *et al.*, 2022). Broader reviews emphasize that frozen-meat quality cannot be inferred from thawing time alone (Zhang *et al.*, 2023; Jiang *et al.*, 2025). Consequently, a single heated chamber configured for both fruit dehydration and thawing should be assessed using task-specific response indicators.

An earlier prototype using incandescent bulbs rated at 60–150 W demonstrated the feasibility of a compact, low-cost heated chamber for food processing (Lamaega *et al.*, 2026). However, the thermal effects of switching between internally recirculated and exhausted air, and the usefulness of an interchangeable ambient-air intake module for thawing, remained insufficiently characterized in that device. The applied contribution of the present study is therefore the assessment of a common small chamber with interchangeable airflow paths rather than the development of a new primary heat source.

This study aimed to (i) quantify the effects of heating power, recirculation versus exhaust mode, and one versus two active modules on chamber thermal response and 15-min electricity consumption under no-load conditions; and (ii) provide descriptive functional tests of exhaust-assisted fruit dehydration and ambient-air-intake thawing. The resulting evidence is intended to inform further design of compact processing equipment for agricultural commodities and food materials under limited power availability.

MATERIAL AND METHODS

Processing Chamber and Airflow Modules

The experiments were conducted during 2025–2026 at the Agroecotechnology Laboratory, Faculty of Agriculture, Universitas Sam



Ratulangi, Manado, Indonesia, under indoor conditions reported as 27 ± 1 °C. The insulated chamber had nominal internal dimensions of $25 \times 25 \times 25$ cm (approximately 15.6 L). Commercial E27 incandescent bulbs rated at 60, 100, and 150 W were installed near the upper center of the chamber, approximately 12–15 cm above a stainless-steel mesh tray. Air was moved by 12 V direct-current axial fans (rated at 0.18 A) installed in removable side cartridges.

Three airflow configurations were used. In recirculation mode, air was withdrawn from an upper port and directed back through a lower port beneath the tray. In exhaust mode, air was discharged from the upper region and the lower return path was closed. In forced

ambient-air intake mode, room-temperature air entered the heated chamber and excess air exited via an upper vent. The setting termed Low used one active fan module, whereas High used two modules operated at the same nominal 12 V supply. These labels indicate module number, not measured air velocity or volumetric flow, because neither flow quantity was determined.

The exhaust and ambient-air intake cartridges are illustrated in Figure 1; the recirculation route is described in the preceding paragraph. The configurations share a standardized side-port interface, allowing the airflow function to be changed without modifying the primary chamber.

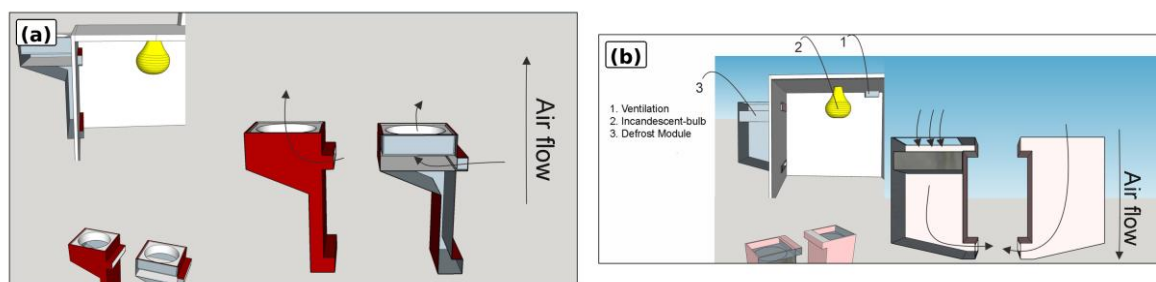


Figure 1. Interchangeable airflow cartridges: (a) exhaust module; (b) forced ambient-air intake module. Arrows show the intended flow direction. Panel (b): 1 = ventilation, 2 = incandescent bulb, and 3 = thawing module. The recirculation path is described in the text.

Factorial Thermal and Energy Experiment

The no-load thermal experiment followed a $3 \times 2 \times 2$ factorial arrangement: lamp power (60, 100, and 150 W), airflow mode (recirculation or exhaust), and active-module setting (Low or High). The 12 combinations were evaluated with three independent runs per condition. The chamber was preheated for 5 min before each run. During the reported 15-min no-load observation interval, temperature was recorded at 1-min intervals with a calibrated digital thermometer (reported accuracy ± 1 °C) positioned at the center of the tray region. Stabilization was operationally defined as a change of less

than 1 °C over three consecutive minutes. Electrical energy was recorded with an inline digital power meter (reported measurement accuracy approximately ± 1 Wh). Whether preheating electricity was included in the meter's cumulative reading was not specified in the retained experimental record; the reported 15-min-cycle totals are therefore presented without further adjustment.

The center-of-tray temperature was the principal directly monitored temperature endpoint. Available upper- and lower-zone readings were used to describe an apparent vertical difference, $\Delta T = T_{\text{max}} - T_{\text{min}}$, but simultaneous independent upper and lower sensor

measurements were not available for each run. Accordingly, ΔT is retained as a descriptive indicator of the reported temperature distribution rather than treated as a separately validated inferential outcome.

Fruit Dehydration Trial

Fresh citrus and strawberry fruits were prepared as slices approximately 4 mm thick. Each described batch consisted of ten slices with an initial mass of approximately 50.00 g. The fruit batches were processed using the exhaust configuration at 60, 100, and 150 W under Low and High module settings. Initial and final batch mass, processing time, and electrical consumption were recorded. Gravimetric mass loss was calculated as $100 \times (W_i - W_f)/W_i$ (%), average mass-removal rate as $(W_i - W_f)/t$ (g min⁻¹), and specific energy consumption (SEC) as $E/(W_i - W_f)$ (Wh g⁻¹ removed mass), where W_i and W_f denote initial and final mass (g), t denotes processing time (min), and E is electrical energy (Wh). These measures represent overall mass changes; final moisture content and water activity were not assessed.

Frozen-Meat Thawing Trial

Frozen meat portions of approximately 100 g, stored at -18 °C, were processed in the forced ambient-air intake configuration at the same three heater-power levels and two module settings. The reported operational endpoint was reached when the central portion was judged no longer visibly or physically frozen, while obvious surface cooking was avoided. Processing time, total mass loss, electricity consumption, and visual observations were recorded. Because product-core temperature and instrument-based color were not measured, these data are presented as operational and descriptive indicators rather than a comprehensive assessment of thawing quality.

Statistical Analysis and Reporting

Center temperature, stabilization time, and electrical consumption from the no-load factorial experiment were analyzed by three-way analysis of variance (ANOVA) using IBM SPSS Statistics version 27, with $\alpha = 0.05$. Shapiro–Wilk and Levene tests were used to assess normality and homogeneity of variance, respectively. The available F and p values are reported without additional recalculation. Upper-to-lower temperature differences, fruit dehydration, and meat thawing are interpreted descriptively. The retained dehydration and thawing records consist of treatment summaries rather than original replicate-level observations; therefore, inferential significance is not claimed for those functional trials..

RESULTS AND DISCUSSION

Thermal Response and Energy Consumption

Heating power and airflow configuration were associated with different chamber temperatures in the no-load test. The reported average center temperatures for recirculation were 53.0–54.0 °C at 60 W, 85.5–87.0 °C at 100 W, and 113.3–115.0 °C at 150 W. For exhaust operation, the corresponding ranges were 47.5–49.0, 75.5–78.0, and 99.0–102.0 °C, respectively. These treatment-level ranges show that recirculation retained more heat within the chamber than exhaust at comparable lamp power.

The reported apparent vertical temperature differences, stabilization times, and energy readings are summarized in Table 1. When High rather than Low recirculation was used, apparent ΔT decreased from 6.8 to 3.2 °C at 60 W, from 10.3 to 4.2 °C at 100 W, and from 13.2 to 5.0 °C at 150 W. Using the rounded table entries, these correspond to approximate reductions of 53%, 59%, and 62%, respectively. Because these upper-to-lower differences were not consistently obtained from independent simultaneous sensor channels, they are treated as



indicative of spatial temperature redistribution, not definitive proof of uniformity throughout the chamber.

Table 1. Apparent temperature difference, stabilization time, and electrical use in 15-min no-load tests (reported mean $\pm$ SD; $n = 3$).

Mode	Power (W)	Modules	Apparent ΔT ($^{\circ}C$)	Stabilization (min)	Energy (Wh/15 min)
Recirculation	60	Low	6.8 ± 0.3	10.47 ± 0.15	15.53 ± 0.06
Recirculation	60	High	3.2 ± 0.3	10.08 ± 0.04	16.07 ± 0.06
Recirculation	100	Low	10.3 ± 0.3	6.80 ± 0.10	25.53 ± 0.06
Recirculation	100	High	4.2 ± 0.3	6.25 ± 0.05	26.07 ± 0.06
Recirculation	150	Low	13.2 ± 0.3	5.40 ± 0.10	38.03 ± 0.06
Recirculation	150	High	5.0 ± 0.0	4.90 ± 0.05	38.57 ± 0.06
Exhaust	60	Low	6.8 ± 0.3	11.17 ± 0.15	15.53 ± 0.06
Exhaust	60	High	6.0 ± 0.0	11.50 ± 0.10	16.07 ± 0.06
Exhaust	100	Low	10.0 ± 0.0	7.50 ± 0.10	25.53 ± 0.06
Exhaust	100	High	8.5 ± 0.0	7.80 ± 0.10	26.07 ± 0.06
Exhaust	150	Low	13.0 ± 0.0	5.80 ± 0.10	38.03 ± 0.06
Exhaust	150	High	11.0 ± 0.0	6.00 ± 0.10	38.57 ± 0.06

Note. Low = one active module; High = two active modules. ΔT = apparent upper-to-lower temperature difference. The precision of some stabilization and energy summaries exceeds the nominal resolution described for the instruments and requires confirmation from the experimental record.

The original factorial ANOVA results are presented in Table 2. Heating power was associated with differences in center temperature, stabilization time, and reported energy use (all $p < 0.001$). Airflow mode affected center temperature and stabilization time, whereas the reported energy consumption did not vary by airflow mode at a fixed heater power and module count ($p = 1.000$). Module setting had reported effects on all three primary responses. The mode $\times$ module-

setting interaction was reported as significant for both center temperature and stabilization, indicating that the consequence of a second active module depended on whether air was recirculated or exhausted. A three-way interaction was also reported for center temperature ($p = 0.018$); broad statements about the effect of module number should therefore remain conditional on the particular power and airflow configuration.

Table 2. Reported three-way factorial ANOVA for no-load thermal and electrical responses.

Factor / interaction	Center F	p	Stabilization F	p	Energy F	p
Power	49,297.32	<0.001	8,616.69	<0.001	457,500.00	<0.001
Airflow mode	4,152.89	<0.001	840.14	<0.001	0.00	1.000
Airflow setting	10.32	0.004	8.79	0.007	768.00	<0.001
Power $\times$ mode	273.25	<0.001	11.72	<0.001	0.00	1.000
Power $\times$ airflow	0.68	0.517	1.28	0.296	0.00	1.000
Mode $\times$ airflow	160.32	<0.001	125.41	<0.001	0.00	1.000
Power $\times$ mode $\times$ airflow	4.75	0.018	0.49	0.616	0.00	1.000

Note. F and p values are reproduced from the retained statistical summary; degrees of freedom and diagnostic-test values were not included in that summary. Power = lamp wattage; mode = recirculation or exhaust; module setting = Low or High.

The 15-min electricity readings ranged from 15.53 to 16.07 Wh for 60 W operation and from 38.03 to 38.57 Wh for 150 W operation. At each power level and

mode, adding a second active fan module increased the reported consumption by approximately 0.54 Wh. The reported energy values were numerically identical



between recirculation and exhaust at the same power and module setting; this should be interpreted as a feature of the reported readings rather than a general proof that airflow direction never affects total electrical demand. Previous studies likewise identify air distribution and thermal management as important elements of dryer performance (Sabat *et al.*, 2021; El-Mesery *et al.*, 2023).

Descriptive Fruit Dehydration Performance

Fruit dehydration was assessed under the exhaust arrangement. Table 3

shows the recorded treatment summaries. At 150 W with two active modules, citrus and strawberry batches had the greatest gravimetric mass losses (69.0% and 67.6%) and the highest average mass-removal rates (1.150 and 1.127 g min⁻¹) among the reported conditions. The power settings also corresponded to different durations: 60 min at 60 W, 45 min at 100 W, and 30 min at 150 W. Accordingly, these results compare the tested combinations of power, module setting, and time; they do not isolate the influence of heater power from duration.

Table 3. Descriptive fruit dehydration results for citrus and strawberry slices.

Material	Power (W)	Modules	Time (min)	Energy (Wh)	Mass loss (%)	Mass loss rate (g/min)
Citrus	60	Low	60	60	33.0	0.275
Citrus	60	High	60	64	39.6	0.330
Citrus	100	Low	45	76	51.0	0.567
Citrus	100	High	45	80	58.4	0.649
Citrus	150	Low	30	76	63.6	1.060
Citrus	150	High	30	79	69.0	1.150
Strawberry	60	Low	60	60	30.4	0.253
Strawberry	60	High	60	64	38.0	0.317
Strawberry	100	Low	45	76	48.8	0.542
Strawberry	100	High	45	80	57.0	0.633
Strawberry	150	Low	30	76	62.0	1.033
Strawberry	150	High	30	79	67.6	1.127

Note. Values are reported treatment summaries, not statistically compared means. Initial batch mass was approximately 50 g; the reported rate represents total mass lost per unit time, not a directly measured water-removal flux.

For the two-module exhaust condition, the original SEC summaries decreased from approximately 3.23 to 2.29 Wh g⁻¹ removed mass for citrus and from 3.37 to 2.34 Wh g⁻¹ for strawberry when the setting changed from 60 to 150 W. Figure 2 illustrates the reported relationship between SEC, nominal heating power, and module number. These values describe electricity consumed per

gram of total gravimetric mass loss; they should not be interpreted as energy per gram of independently measured moisture removed. The lower SEC recorded at 150 W under the tested processing durations is consistent with the need to interpret useful mass removal together with energy consumption, as discussed in drying research (Martynenko & Vieira, 2023; Meng *et al.*, 2022).



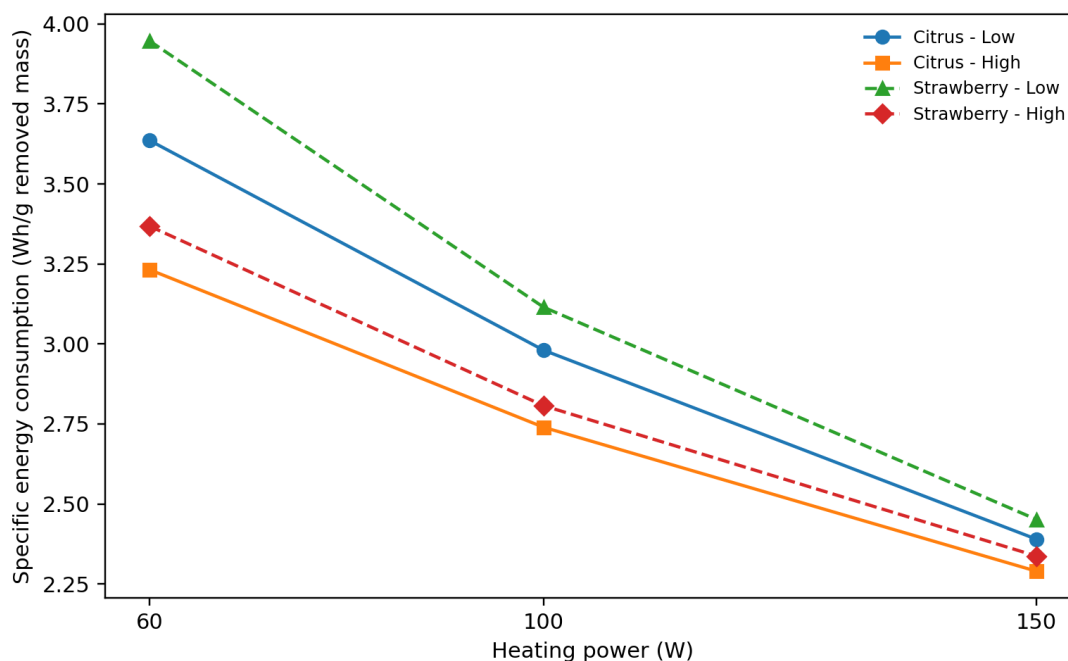


Figure 2. Reported specific energy consumption in fruit dehydration for Low and High exhaust-module settings. SEC is expressed per gram of gravimetric mass loss.

The original experimental notes also describe less visible edge browning under High exhaust than under Low exhaust at 150 W. This is a qualitative observation rather than an instrumental color measurement. Consequently, it may motivate subsequent product-quality assessment but does not establish a quantitative advantage in color preservation.

Descriptive Forced-Air Thawing Performance

For thawing with ambient-air intake, the recorded operational endpoint was

reached after 20 min (Low) or 15 min (High) at 60 W and after 15 min (Low) or 12 min (High) at 100 W. At 150 W, both settings reached the recorded endpoint in 10 min (Table 4). Figure 3 depicts these treatment-level observations. The reported reduction in endpoint time with two modules was accompanied by different recorded mass-loss percentages: 2.2% versus 2.8% at 60 W and 4.0% versus 4.6% at 100 W for Low versus High, respectively. Faster observed thawing therefore did not imply lower mass loss under these conditions.

Table 4. Descriptive thawing results with forced ambient-air intake.

Power (W)	Modules	Endpoint time (min)	Energy (Wh)	Mass loss (%)
60	Low	20	21	2.2
60	High	15	16	2.8
100	Low	15	26	4.0
100	High	12	21	4.6
150	Low	10	25	6.5
150	High	10	26	6.0

Note. Endpoint time was based on the study's physical/visual operational criterion, not measured product-core temperature. Values are descriptive treatment summaries; no inferential comparisons are reported.

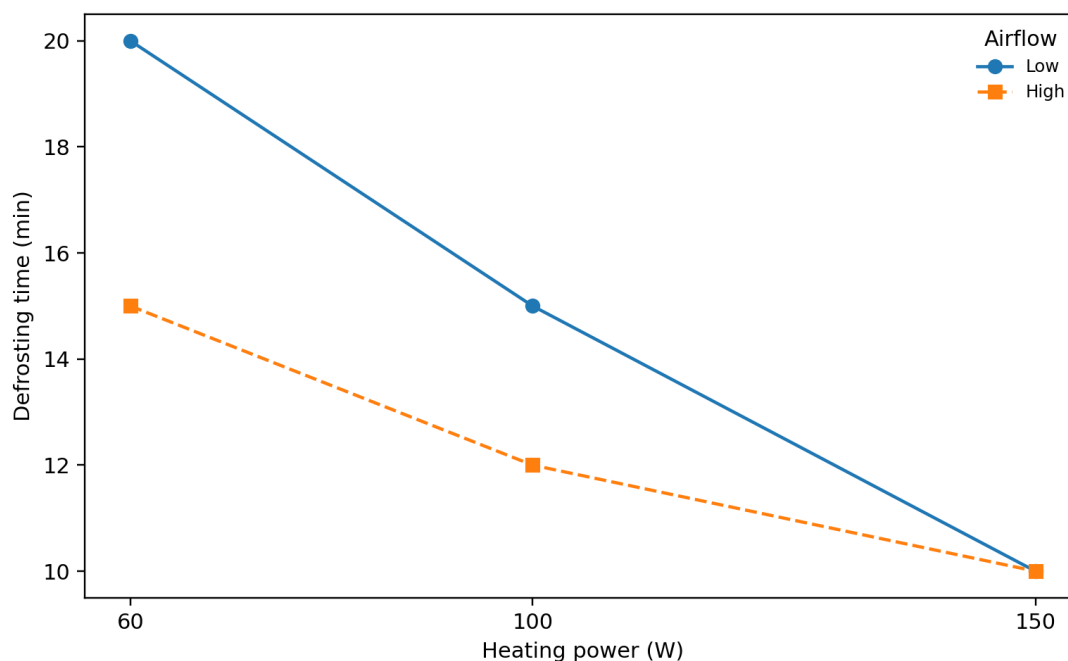


Figure 3. Recorded time to the operational thawing endpoint under Low (one module) and High (two modules) ambient-air intake.

The qualitative observations described a softer center at 60 W with Low airflow and more complete central thawing under High airflow. At 100 W, High airflow was described as producing more even thawing, whereas at 150 W the Low setting showed greater edge color change. Such observations suggest a practical trade-off between endpoint time and visible surface condition, but the interpretation is limited by the visually judged endpoint, unspecified meat characteristics, and lack of direct core-temperature or instrumental color measurements. The findings should not be equated with verified thawing uniformity or meat safety. Previous studies similarly distinguish time-based thawing performance from broader quality outcomes (Lee *et al.*, 2021; Gan *et al.*, 2022; Zhang *et al.*, 2023; Jiang *et al.*, 2025).

Applied Relevance and Study Limitations

The main practical contribution is a compact chamber whose function is

changed by altering an interchangeable airflow path: recirculation favors heat retention, exhaust permits moisture-laden air to leave the chamber, and ambient-air intake supports operational thawing. For small-batch agricultural and food processing, this flexibility is relevant where equipment space and available electrical power are limited. The study does not establish commercial-scale performance, food shelf life, microbial safety, or an overall environmental advantage.

Several limitations require explicit recognition. Low and High denote one and two active fan modules rather than quantified air velocities. The apparent vertical temperature difference was derived from nonuniformly available spatial readings and was analyzed descriptively. Dehydration and thawing records were retained as treatment summaries, and the processing duration varied with heater power in the fruit tests. The thawing endpoint was assessed physically and visually rather than by direct measurement of core temperature.

Finally, the precise basis of the preheating energy, the unusually fine precision of certain summarized instrument readings, and the details of functional-trial replication cannot be confirmed from the supplied records. These limitations motivate careful interpretation and further engineering validation rather than changes to the reported data

CONCLUSION

Interchangeable airflow modules changed the behavior of a compact chamber using incandescent heaters rated at 60–150 W. In the no-load trials, recirculation maintained higher center temperatures than exhaust and the two-module recirculation setting showed a smaller apparent upper-to-lower temperature difference. Under the tested fruit-processing schedules, 150 W with two exhaust modules produced the largest recorded gravimetric mass losses and lowest reported specific energy use per gram of removed mass. In the descriptive thawing trials, two ambient-air intake modules shortened the observed operational endpoint at 60 and 100 W, although they were associated with greater mass loss in those conditions. The findings support the potential use of interchangeable airflow paths in compact agricultural-product and food-processing equipment; further measurements of actual airflow, product temperature, moisture status, and quality are needed before optimization or scale-up can be established.

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