

Fabrication and Performance Evaluation of a Semi-Automatic Electric Cabinet Dryer for Carrot, Cabbage and Tomato

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Abstract

Post-harvest losses of perishable vegetables limit food security and farm income in many low-income settings, and low-cost, controllable dryers can help to reduce them. This study aimed to design, fabricate and test a semi-automatic electric cabinet dryer and to compare its performance on three vegetables. The dryer is a 60 × 40 × 40 cm wooden cabinet that was modelled in SolidWorks and fitted with a 500 W resistive heating element, a fan, wire-mesh trays, a temperature and humidity controller and a mini-controller. Carrot, cabbage and tomato were each dried in five replicate 16-min runs at chamber temperatures of 49–55°C, and sample mass was recorded before and after each run. Mean moisture loss, expressed as a percentage of initial mass, was $29.6 \pm 7.9\%$ for carrot, $45.6 \pm 4.3\%$ for cabbage and $15.0 \pm 1.0\%$ for tomato (mean $\pm$ SD, $n = 5$), equivalent to mean drying rates of 1.85, 2.85 and $0.94\% \text{ min}^{-1}$. Moisture loss differed significantly among crops (Welch's ANOVA, $p < 0.001$) and all pairwise differences were significant (Games–Howell, $p < 0.05$), although the tomato runs were also conducted at a lower chamber humidity (about 32% versus 46%). The fabrication cost was 84,755 Rwf, and electrical components accounted for 86% of the hardware cost. Because the trials were short and did not include final moisture content, product quality or metered energy, the results demonstrate functional performance and relative crop behaviour rather than optimum drying conditions. Longer, instrumented trials with metered energy are the necessary next step.

1. Introduction

Fresh vegetables are highly perishable, and a large share of the food produced for human consumption is lost before it is eaten: roughly one-third is lost or wasted along the food chain worldwide (Gustavsson et al., 2011). The point at which losses concentrate differs between regions; in low-income regions, handling and storage are a hotspot, whereas in high-income regions losses are more prominent at the consumption stage (Flanagan et al., 2019). In low-income countries the causes are mainly financial, managerial and technical limitations in harvesting, storage and cooling (Gustavsson et al., 2011). Such losses waste the land, water and energy invested in production, at a time when water scarcity already constrains agricultural output in many regions (Dinar et al., 2019; Vallino et al., 2020). Reducing post-harvest losses of fruits and vegetables is therefore regarded as a component of more sustainable food systems and as a route to improved food security (Cassani & Gomez-Zavaglia, 2022; Nguyen, 2018; Rajapaksha et al., 2021). Agri-food residues generated during handling and processing are also increasingly recognised as a resource rather than only a waste stream (Voss et al., 2024).

In Rwanda, agriculture is central to the economy and to rural livelihoods (Rispoli et al., 2019), and the management of water resources for farming remains a recognised concern (Hakiruwizera et al., 2022). Smallholder producers who cannot store or process surplus vegetables are often exposed to spoilage and to low prices at the peak of the harvest. Preservation by drying is one practical response. Removing water lowers the susceptibility of the product to microbial and biochemical deterioration, reduces mass and volume for storage and transport, and allows surplus produce to be sold or consumed out of season (Jayaraman & Gupta, 2020; Mercer, 2014). Traditional open-air drying, however, is slow, depends on the

weather and exposes the product to contamination, and the choice of drying method strongly influences the nutritional and microbiological quality of the dried product (Athira et al., 2023; Verma et al., 2020; Wang et al., 2023).

Convective drying couples the transfer of heat from the air to the product with the movement of moisture from the interior to the surface and then into the air stream; the rate at which this occurs depends mainly on the temperature, humidity and velocity of the air and on the size and structure of the product (Mercer, 2014). Experimental studies of hot-air drying generally report that raising the air temperature shortens the drying time. For carrot, zucchini and eggplant, increasing the air temperature from 60 to 80°C reduced the total drying time by 35% (carrot) to 50% (eggplant), and drying took place entirely in the falling-rate period (Kılıç & Çınar, 2019). For tomatoes dried at 55–70°C, the drying rate increased markedly with temperature (Doymaz, 2007), and for white cabbage dried in hot-air and microwave dryers the specific energy consumption was higher at lower drying temperature (Luka et al., 2023).

A wide range of dryer designs has been reported, from rotary and tray dryers to heat-pump, solar and hybrid systems (de Souza Barrozo et al., 2023; El-Mesery et al., 2022; Kang et al., 2022; Radhakrishnan et al., 2024; Yousaf et al., 2020), and recent reviews summarise novel drying technologies and their effects on product quality (Wu et al., 2024; Yoha et al., 2024). Modern work emphasises sensing and control to hold temperature and humidity near their targets (Martynenko & Bück, 2018), and dryers have been designed and justified for individual crops (Karimov et al., 2020). Drying behaviour is also strongly product-specific: vegetables and spices that differ in structure and composition dry at different rates under the same air conditions (Anjaneyulu & Sharangi, 2022b; Kılıç & Çınar, 2019; Krokida et al., 2003). Finally, drying is energy intensive, so energy use is an essential performance criterion alongside drying rate (Kudra, 2004; Menon et al., 2020).

Most of this literature concerns laboratory dryers or comparatively sophisticated systems. Small, locally fabricated electric cabinet dryers are attractive for small processors and training institutions because they use inexpensive materials and operate independently of the weather, but in the literature reviewed for this study quantitative reports of their moisture-removal performance and energy use on several vegetables under identical conditions were limited. Without such information, small-scale users cannot judge which crops a simple dryer handles well or how much electricity a batch requires. Generating it has practical value in Rwanda and similar settings: it supports the selection of crops and operating practices for small-scale drying, provides cost and energy benchmarks for local fabrication, and gives training institutions a documented design that students can reproduce and improve.

The aim of this study was to design, fabricate and test a semi-automatic electric cabinet dryer for vegetables. The specific objectives were (i) to design the dryer as a three-dimensional model; (ii) to fabricate it from locally available materials; and (iii) to evaluate its performance by measuring chamber temperature and humidity, moisture loss, drying rate and energy consumption for carrot, cabbage and tomato. We tested the hypothesis that, under the same operating conditions, moisture loss differs among the three crops.

2. Materials and Methods

2.1 Dryer design and components

The dryer was designed as a rectangular wooden cabinet with nominal dimensions of 60 × 40 × 40 cm (external) and 58 × 38 × 38 cm (internal). The design followed five steps: installation of the SolidWorks 2025 computer-aided design package; training in its sketching, part-modelling and assembly tools; identification of the main components (heating element, fan, control panel and trays) and of how they fit within the specified dimensions; three-dimensional visualisation of the layout; and preparation of detailed technical drawings that guided fabrication.

The dryer works on the forced-convection principle. A resistive electric heating element rated at 500 W heats the air in the drying chamber, a fan circulates the warm air across wire-mesh trays, and moisture-laden air leaves through a vent. Temperature and humidity sensors monitor the chamber, and a mini-controller allows the operator to set the drying temperature and time. Loading, unloading and periodic checking of the product are done manually, which makes the system semi-automatic rather than fully automatic. The components are listed in Table 1.

Table 1
Components and specification of the semi-automatic electric cabinet dryer.

Component	Specification	Function
Cabinet	Wooden box, 60 × 40 × 40 cm (external), 58 × 38 × 38 cm (internal)	Drying chamber and structure
Heating element	Resistive element, rated 500 W, 220 V AC	Heat source
Fan	12 V, 0.4 A	Air circulation through the chamber
Trays	Wire mesh on wooden frames; three trays spaced 15 cm apart	Support for the product
Sensors	XH-M452 temperature and humidity controller; range – 40 to 120°C and 0–100% RH	Monitoring of chamber conditions
Mini-controller	Control panel with temperature and time setting (0–100%)	Operator interface; switching of heater and fan
Power supply	Adapter and electrical wiring	Power distribution to the components

2.2 Fabrication

Fabrication followed the technical drawings and comprised five operations: (i) measuring and marking the timber with a tape measure and T-square and cutting it with a hand saw, a machete and a vibrating saw; (ii) joining the parts by nailing, using clamps to hold pieces in place; (iii) connecting the electrical

system, i.e. wiring the heating element, fan, sensors and controller according to a wiring diagram and insulating exposed connections; (iv) checking the working condition of all components, including unusual noise or overheating; and (v) final adjustment and finishing. The work was carried out by the authors at RP Gishari College carpentry workshop (Fig. 2).

2.3 Experimental design and sample preparation

The performance test was a single-factor experiment with crop type (carrot, cabbage or tomato) as the treatment and five replicate runs per crop (15 runs in total). Each run lasted 16 min. Fresh produce bought at a market was washed and peeled, weighed (Fig. 2c) and loaded on the trays; about 300 g of produce was loaded for each run. 2mm width and 5 mm length, whether any blanching was applied, and how the 300 g tray load relates to the nominal 100 g sample mass. The dryer was pre-heated for 6 min before loading. Sample mass was recorded before drying (W_1 ; nominal value 100 in all runs, in g) and immediately after the 16-min run (W_2) with a digital balance (g). Balance model SF-400, capacity: 10000g $\times$ 1g/3530Zx0.1oz. Chamber temperature ($^{\circ}\text{C}$) and relative humidity (%) were read from the sensor of the XH-M452 temperature and humidity controller (range – 40 to 120 $^{\circ}\text{C}$ and 0–100% RH) every 2 min, giving eight readings per run. The heating element was rated at 500 W. Test occur on 3rd, June-October, 2026, in RP-Gishari college. Chamber humidity was not controlled, so it differed between crops (Section 3.2).

2.4 Moisture loss and drying rate

The moisture loss of a sample during a run was expressed in two ways (Eqs. 1 and 2):

$$\text{ML}_{\text{wb}} = \frac{W_1 - W_2}{W_1} \times 100$$

1

$$\text{ML}_{\text{f}} = \frac{W_1 - W_2}{W_2} \times 100$$

2

where W_1 and W_2 are the sample masses before and after drying. ML_{wb} is the percentage of the initial mass lost during the run. ML_{f} expresses the same loss relative to the final mass, i.e. the final mass W_2 is used in place of the bone-dry mass. Because the bone-dry mass and the initial moisture content were not determined (for example, by oven drying), ML_{f} is not a true dry-basis moisture content, and the results are interpreted as mass (moisture) loss during a fixed 16-min exposure. The mean drying rate over a run, R ($\% \text{ min}^{-1}$), was calculated for each basis as (Eq. 3):

$$R = \frac{ML}{t}$$

with $t = 16$ min. Rates were not extrapolated to 60 min, because the extrapolation lies far outside the observed interval.

2.5 Energy consumption

Energy consumption (E , kWh) was estimated from the rated power of the heating element ($P = 0.5$ kW) and the reported operating time ($t_{\text{op}} = 4.5$ h) (Eq. 4):

$$E = P \times t_{\text{op}}$$

giving 2.25 kWh as an upper-bound estimate. The estimate assumes continuous operation at rated power, excludes the fan and controller, and was not metered. 4 hrs of drying plus pre-heating 0.5 then equal to 4.5hrs. If it is the total for all runs, the energy attributable to each crop ($5 \times 16 = 80$ min of drying) is about one third of this value, i.e. 0.75 kWh. Because the same value applies to all crops, no energy-based index was calculated to compare them.

2.6 Statistical analysis

Results are presented as mean $\pm$ standard deviation (SD) of the five replicate runs. The effect of crop on moisture loss (ML_{wb}) was tested by one-way Welch's analysis of variance, which does not assume equal variances, followed by Games–Howell pairwise comparisons; the classical one-way ANOVA was used as a check. Differences in mean chamber temperature and humidity among crops were analysed in the same way. The significance level was $\alpha = 0.05$, and the effect size is given as η^2 . Analyses were performed in Python with the SciPy library. Because there were only two mass measurements per run, drying curves and kinetic models were not fitted.

3. Results and Discussions

3.1 Fabricated dryer and cost

The design stage produced a three-dimensional model of a cabinet with a hinged door, vertically stacked trays and a control module mounted on top (Fig. 1). The fabricated prototype followed this layout (Fig. 2a), with the controller, sensors, heating element and fan wired into the cabinet (Fig. 2b), and it was used for the 15 test runs described below. The itemised cost of the project was 84,755 Rwf, including a 10% contingency (Table 2). The hardware (heating element, controller, adapter, fan, wire mesh, timber and wiring), excluding labour and test produce, cost 63,250; the heating element (47%) and the controller (24%) together accounted for 71% of this amount, and all electrical items for 86%.

Table 2
Itemised cost of the dryer project (currency: Rwf).

No.	Item	Quantity	Unit cost	Cost
1	Controller	1	15,000	15,000
2	Adapter	1	3,500	3,500
3	Heating element	1	30,000	30,000
4	Fan	1	5,000	5,000
5	Wire mesh	1.5m	2,500	3,750
6	Test produce	3	600	1,800
7	Timber	2	2,500	5,000
8	Electrical wires	1	1,000	1,000
9	Labour	2	6,000	12,000
Subtotal				77,050
Contingency (10%)				7,705
Total				84,755

3.2 Chamber temperature and humidity

In all 15 runs, the chamber temperature rose steadily during the 16-min test (Fig. 3a). The first reading, at 2 min, was 49.0–50.2°C and the last, at 16 min, 52.6–55.0°C, a mean increase of 4.2, 4.3 and 5.1°C for carrot, cabbage and tomato, respectively. No reading exceeded 55.0°C, and five runs (four tomato runs and one carrot run) reached exactly 55.0°C at the last reading. Mean chamber temperatures were $51.86 \pm 0.61^\circ\text{C}$ for carrot, $51.89 \pm 0.58^\circ\text{C}$ for cabbage and $52.71 \pm 0.71^\circ\text{C}$ for tomato, which did not differ significantly (Welch's $F(2, 7.94) = 2.34, p = 0.159$).

Chamber humidity, by contrast, differed among crops (Fig. 3b). It averaged $46.81 \pm 3.67\%$ for carrot and $46.18 \pm 0.86\%$ for cabbage, but only $32.43 \pm 2.47\%$ for tomato (Welch's $F(2, 6.15) = 63.0, p < 0.001$). Humidity in the tomato runs was significantly lower than in the carrot and cabbage runs (both $p < 0.001$), whereas carrot and cabbage did not differ ($p = 0.93$). Humidity therefore covaried with crop and must be taken into account when comparing crops.

3.3 Moisture loss and drying rate

Table 3 lists the results of the 15 runs and Table 4 summarises them by crop. In 16 min, carrot, cabbage and tomato lost on average 29.6, 45.6 and 15.0% of their initial mass (Fig. 4a); the final sample mass, from a nominal initial mass of 100, was 70.4 ± 7.9 , 54.4 ± 4.3 and 85.0 ± 1.0 , respectively. Mean drying

rates were 1.85, 2.85 and 0.94% min⁻¹ on the initial-mass basis (Fig. 4b) and 2.72, 5.30 and 1.10% min⁻¹ when the loss was expressed relative to final mass (Table 4).

Crop had a very large and significant effect on ML_{wb} (Welch's $F(2, 5.69) = 114.5, p < 0.001, \eta^2 = 0.88$; classical ANOVA $p < 0.001$). Cabbage lost significantly more moisture than carrot ($p = 0.017$) and tomato ($p < 0.001$), and carrot lost significantly more than tomato ($p = 0.031$); the null hypothesis of no difference among crops was therefore rejected. The ranges of the individual runs did not overlap (tomato 14–16%, carrot 19–41%, cabbage 42–52%). Variability among replicates was much greater for carrot (coefficient of variation, CV = 27%) than for cabbage (9%) or tomato (7%).

Some entries in the summary records of the cabbage runs and of one tomato run were internally inconsistent (note to Table 3). They were corrected using the measured final masses ($ML_{wb} = 100 - W_2$) and the means of the eight sensor readings of each run, and the corrected values are used throughout. Had the uncorrected entries been used, the cabbage mean would have been $44.8 \pm 2.9\%$ (2.80% min⁻¹); the effect of crop and the pairwise conclusions would not have changed.

Table 3

Results of the 15 drying runs (16 min each): mean chamber temperature (T) and humidity (RH), final sample mass (W_2 ; nominal initial mass $W_1 = 100$), moisture loss relative to initial mass (ML_{wb}) and relative to final mass (ML_f). Corrected entries are explained in the note below the table.

Crop	Run	T (°C)	RH (%)	W_2	ML_{wb} (%)	ML_f (%)
Carrot	1	51.08	50.95	81	19	23.46
	2	51.63	50.62	73	27	36.99
	3	52.71	43.70	69	31	44.93
	4	52.18	43.72	70	30	42.86
	5	51.72	45.07	59	41	69.49
Cabbage	1	51.28	46.34	57	43	75.44
	2	51.73	47.55	57	43	75.44
	3	51.60	45.73	58	42	72.41
	4	52.05	45.26	52	48	92.31
	5	52.80	46.01	48	52	108.33
Tomato	1	51.48	36.30	84	16	19.05
	2	53.19	32.93	86	14	16.28
	3	52.73	32.34	85	15	17.65
	4	52.99	30.29	86	14	16.28
	5	53.18	30.29	84	16	19.05

Note: Values were corrected where the summary records were inconsistent with the replicate sheets: ML_f was recalculated from the measured W_2 (cabbage runs 2 and 4); T and RH are the means of the eight readings of the run (cabbage runs 3 and 5; tomato run 1); and W_2 and ML_{wb} of cabbage run 5 (48 and 52) had been transposed. Tomato runs 4 and 5 have identical RH (30.29).

Table 4

Summary of chamber conditions, moisture loss and mean drying rate by crop (mean $\pm$ SD, $n = 5$ runs; 16-min runs).

Crop	T (°C)	RH (%)	W ₂	ML _{wb} (%)	ML _f (%)	R _{wb} (% min ⁻¹)	R _f (% min ⁻¹)
Carrot	51.86 $\pm$ 0.61	46.81 $\pm$ 3.67	70.4 $\pm$ 7.9	29.6 $\pm$ 7.9 ^b	43.5 $\pm$ 16.7	1.85 $\pm$ 0.50	2.72 $\pm$ 1.05
Cabbage	51.89 $\pm$ 0.58	46.18 $\pm$ 0.86	54.4 $\pm$ 4.3	45.6 $\pm$ 4.3 ^a	84.8 $\pm$ 15.3	2.85 $\pm$ 0.27	5.30 $\pm$ 0.96
Tomato	52.71 $\pm$ 0.71	32.43 $\pm$ 2.47	85.0 $\pm$ 1.0	15.0 $\pm$ 1.0 ^c	17.7 $\pm$ 1.4	0.94 $\pm$ 0.06	1.10 $\pm$ 0.09

ML_{wb} and ML_f: moisture loss relative to initial and final mass, respectively; *R*: mean drying rate (ML divided by 16 min). Different superscript letters indicate significant differences in ML_{wb} (Games–Howell, $p < 0.05$).

3.4 Energy consumption

The estimated electrical energy input, based on the rated heater power and 4.5 h of operation, was 2.25 kWh (Section 2.5); if this time covers all 15 runs, the input per crop was about 0.75 kWh. Because the same value applies to every crop and the energy was not metered, no crop-specific energy performance can be derived from the present data. The ranking of the crops by moisture loss and drying rate (cabbage > carrot > tomato) does not depend on the assumed energy.

4. Discussion

4.1 Functional performance of the dryer

The dryer reached 49–50°C at the first 2-min reading and warmed by a mean of 4.2–5.1°C during the 16-min runs, never exceeding 55.0°C (Section 3.2). After a 6-min pre-heating period, the 500 W element and the fan were therefore sufficient to keep the 60 × 40 × 40 cm wooden chamber at a temperature suitable for vegetable drying throughout the runs. These temperatures lie at or below the lower end of the ranges used in published laboratory studies, for example 55–70°C for tomatoes (Doymaz, 2007) and 60–80°C for carrot, zucchini and eggplant (Kılıç & Çınar, 2019). Because drying rate increased with air temperature in those studies, faster drying would be expected at higher temperatures in the present dryer, within the limits set by product quality (Athira et al., 2023; Verma et al., 2020).

The upper bound of 55.0°C that was observed in all 15 runs, with five runs reaching exactly this value at the last reading, is consistent with a thermostatic cut-off. If confirmed, this would be the element of automatic control in the semi-automatic design (Martynenko & Bück, 2018); the controller set-point is

not documented, however, and this interpretation needs verification. Neither the air velocity nor the temperature distribution among trays was measured. Both matter, because uneven airflow causes uneven drying within a chamber (Mercer, 2014), and they should be mapped before the dryer is recommended for larger loads.

4.2 Crop-specific drying behaviour

Cabbage lost about three times, and carrot about twice, as much of its initial mass as tomato in the same 16-min exposure, and the run-to-run ranges did not overlap between crops. That drying behaviour differs among vegetables under identical air conditions is well established (Anjaneyulu & Sharangi, 2022b; Kılıç & Çınar, 2019; Krokida et al., 2003), so the ranking itself is not surprising; what the present data add is a first quantification for this low-cost dryer.

The experiment was not designed to identify the mechanism, but the literature suggests plausible contributions. In the tomatoes studied by Doymaz, the moisture content was 94.5% (wet basis), and an alkaline ethyl-oleate dip applied before drying increased the effective moisture diffusivity $((5.65-7.53) \times 10^{-10} \text{ m}^2 \text{ s}^{-1})$ versus $(3.91-6.65) \times 10^{-10}$ for untreated fruit (Doymaz, 2007). This is consistent with the skin and tissue structure of tomato imposing a substantial resistance to moisture transport, if the tomatoes in the present study were dried whole or in thick pieces with intact skin (the preparation was not recorded). Effective diffusivities reported for white cabbage in hot-air drying, $(3.26-6.07) \times 10^{-9} \text{ m}^2 \text{ s}^{-1}$ (Luka et al., 2023), are about an order of magnitude higher than those reported for tomato, although the two studies used different materials and conditions and the comparison is only qualitative. Thin, leafy tissue with a large surface-to-mass ratio would be expected to lose moisture faster than whole fruit or thicker pieces. Because the size and shape of the pieces were not recorded, this explanation remains a hypothesis.

Humidity is an important confounder. The chamber humidity during the tomato runs ($32.4 \pm 2.5\%$) was about 14 percentage points lower than during the carrot and cabbage runs (46–47%), while temperatures did not differ significantly. A drier chamber atmosphere increases the vapour-pressure deficit that drives evaporation from the surface, so humidity alone would be expected to favour faster drying of tomato. That tomato nevertheless dried most slowly suggests that the internal resistance of the product, rather than the external driving force, limited its drying rate. Because humidity and crop were not varied independently, this inference is tentative. The low humidity may also be partly a consequence of the small amount of water vapour released by the tomato samples, and ambient conditions on the test days, which were not recorded, may have contributed.

Carrot showed the greatest variability among replicates (19–41%; CV = 27%), three to four times the CV of cabbage (9%) or tomato (7%). Carrot pieces vary in size, and differences in cut geometry, tray position or root maturity could explain this spread; none of these factors was controlled or recorded. Standardising piece size and loading is a prerequisite for fitting drying models and for comparing temperature settings.

4.3 Extent of drying and interpretation of rates

The 16-min runs removed 15–46% of the initial mass, which is far from the extent required for a storage-stable dried vegetable; tomatoes, for example, were dried from 94.5% to 11% moisture (wet basis) by Doymaz (Doymaz, 2007). The rates reported here therefore describe the early stage of drying. Because most drying takes place in the falling-rate period (Kılıç & Çınar, 2019), rates averaged over a complete drying cycle will be lower than those measured here, and the rates should not be extrapolated beyond the 16-min interval. Recording mass at only two time points also precludes estimation of drying curves, effective diffusivities or model parameters, which are commonly reported in the literature (Kılıç & Çınar, 2019; Krokida et al., 2003).

4.4 Energy consumption and cost

The energy estimate of 2.25 kWh was calculated from the rated heater power and the operating time and applies equally to all crops. It has several limitations. First, it assumes continuous operation at rated power, whereas a thermostatically controlled heater would cycle on and off, and it excludes the fan and controller. Second, the 4.5 h of operation is longer than the 80 min of drying per crop; it is close to the 4 h of drying in all 15 runs (15×16 min), which suggests that it may be the total for the whole test series, in which case the energy attributable to each crop would be about one third of the value used (0.75 kWh). Third, the initial sample mass is nominal (100 in all runs), so the mass of water evaporated and the specific energy consumption cannot be calculated reliably. As a benchmark, evaporating water requires at least about 2.4 MJ kg^{-1} (0.66 kWh kg^{-1}) of heat at these temperatures, so a meaningful efficiency can be derived only if the sample mass is recorded in kilograms and the energy is metered.

A more informative indicator is the specific energy consumption, i.e. the energy used per kilogram of water evaporated. For white cabbage it was higher at lower drying temperature (Luka et al., 2023), which indicates that a higher operating temperature, within the limits set by product quality, may reduce the energy needed per unit of water removed. Because drying is energy intensive (Kudra, 2004; Menon et al., 2020), metering of energy and recording of sample mass in kilograms should be standard in future trials of this dryer.

Electrical components made up 86% of the hardware cost (the heating element alone 47%), whereas timber and wire mesh accounted for 14%. Efforts to reduce the cost of a similar unit should therefore target the heater and controller, for example through locally available heating elements and simpler control, rather than the structure, which is already inexpensive. The cost table includes labour and test produce, which are not part of the hardware cost, and a full economic analysis (electricity, maintenance, depreciation and the value of the dried product) was not performed.

4.5 Limitations and implications

The main limitations of the study are the following. Only the initial and final masses were recorded, so drying kinetics could not be analysed. The nominal initial mass of 100 and the absence of oven-determined moisture contents mean that true moisture contents on a wet or dry basis are unknown.

Variety, preparation and geometry of the samples were not standardised or recorded, and chamber humidity was not controlled and covaried with crop. The five replicates per crop may not be fully independent. Energy was estimated rather than measured, and air velocity and temperature uniformity were not determined. Finally, product quality (colour, nutrient retention, rehydration and microbial safety), which governs the value of dried vegetables (Athira et al., 2023; Verma et al., 2020; Wang et al., 2023), was not assessed. Several summary entries had to be corrected against the replicate sheets (Table 3); this did not alter any ranking or statistical conclusion (Section 3.3) but shows the need to record raw data directly in a standard sheet.

Within these limits, the results suggest that at the chamber conditions of this prototype thin-tissue vegetables such as cabbage are dried more readily than tomato, and that tomato may need size reduction or surface pre-treatment to be dried efficiently, as in the dip treatments studied by Doymaz (Doymaz, 2007). Further development should (i) dry each crop to a target moisture content with oven-determined initial moisture; (ii) meter energy and report specific energy consumption; (iii) standardise sample geometry and control humidity; and (iv) assess quality attributes. Hybridising the dryer with solar thermal energy could reduce electricity use (El-Mesery et al., 2022; Radhakrishnan et al., 2024), although the challenges of solar energy adoption in developing countries need to be considered (Bhutto et al., 2012); low-cost internet-of-things sensing and control could improve the semi-automatic operation (Flores-Mendoza et al., 2023; Martynenko & Bück, 2018); and operating parameters could be optimised by multi-objective approaches that balance drying time, energy use and quality (Cerdeira-Flores et al., 2022). Packaging and storage conditions of the dried product also matter, because packaging affects the shelf life of dried vegetables stored under ambient conditions (Anjaneyulu & Sharangi, 2022a) and humid storage environments call for humidity control (Hussain et al., 2022). Dried tomato products such as powders are of commercial interest (Anisuzzaman et al., 2022), and preparation trimmings could be dried and valorised (Voss et al., 2024).

5. Conclusion and Recommendations

A semi-automatic electric cabinet dryer was designed, modeled in 3D, and fabricated from locally sourced timber, wire mesh, and standard electrical components to evaluate its drying performance on perishable vegetables. During 16-minute experimental runs at chamber temperatures ranging between 49°C and 55°C, the prototype successfully demonstrated functional drying capacity across all tested crops. Under comparable thermal conditions, cabbage exhibited the highest moisture loss at 45.6% of initial mass (2.85% min⁻¹), followed by carrot at 29.6% (1.85% min⁻¹), and tomato at the lowest rate of 15.0% (0.94% min⁻¹). Although the differences in moisture loss among crops were statistically significant, the lower relative humidity observed during tomato runs prevents a complete separation of crop-specific structural resistance from chamber humidity effects. In addition, electrical energy consumption was estimated at 2.25 kWh based on nominal heater wattage and total operation time rather than direct metering, limiting exact energy efficiency comparisons.

The total fabrication cost of 84,755 Rwf underscores the economic feasibility of the prototype for small-scale processors and educational institutions in Rwanda. Because electrical components accounted for 86% of the total hardware cost, future cost-reduction strategies should focus on simplifying or locally sourcing the heating and control units rather than modifying the structural frame. Overall, while the study confirms the operational viability of this low-cost cabinet dryer, the short experimental runs mean these findings reflect initial functional performance and relative crop drying dynamics rather than optimized drying schedules, final target moisture levels, or long-term product shelf life.

To build upon these baseline results, future research should focus on extended drying runs that process each crop to a specific target moisture content suitable for safe storage, supported by oven-determined initial moisture measurements. Subsequent studies should integrate dedicated inline energy meters to measure real-time power draw and establish accurate specific energy consumption benchmarks per kilogram of water evaporated. Furthermore, future trials should strictly standardize sample geometry, control chamber humidity independently, and evaluate critical quality parameters including color retention, rehydration ratio, nutrient preservation, and microbial safety.

Declarations

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Regarding author contributions, Soulaïman Mwamini led the conceptualization, research tool development, experimental execution, and primary drafting of the manuscript. Triphonie Uwamariya, Jean Nepo Nsengiyumva, Venant Kubwimana, and Marie Jeanne Umuhoza provided academic supervision, methodological guidance, drafting support, and critical manuscript revisions. Experimental data collection and statistical analysis were performed by Soulaïman Mwamini and Triphonie Uwamariya. All authors read, edited, and approved the final manuscript for publication.

Author Contributions

Ideation and conceptualization: S.M. Supervision and guidance: T.U., J.N.N., V.K. and M.J.U. Development of research and tools: J.N.N., S.M. Data collection and analysis: J.N.N. Study design and methodological rigour: S.M., J.N.N., M.J.U. Drafting and revising the manuscript: S.M., T.U., J.N.N., V.K. Review, editing and proofreading: T.U., J.N.N., V.K. and M.J.U.

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Data Availability

The datasets generated and analysed during the current study are available from the corresponding author on reasonable request at soulaimanmwamini0@gmail.com, or at [doi:10.6084/m9.figshare.29425451](https://doi.org/10.6084/m9.figshare.29425451).

Ethics Approval and Consent to Participate: This study did not involve human participants, human biological tissue, or animal subjects; therefore, formal ethical approval and informed consent were not required.

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Figures

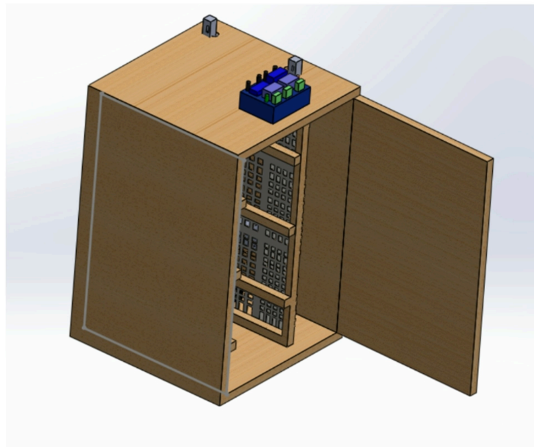
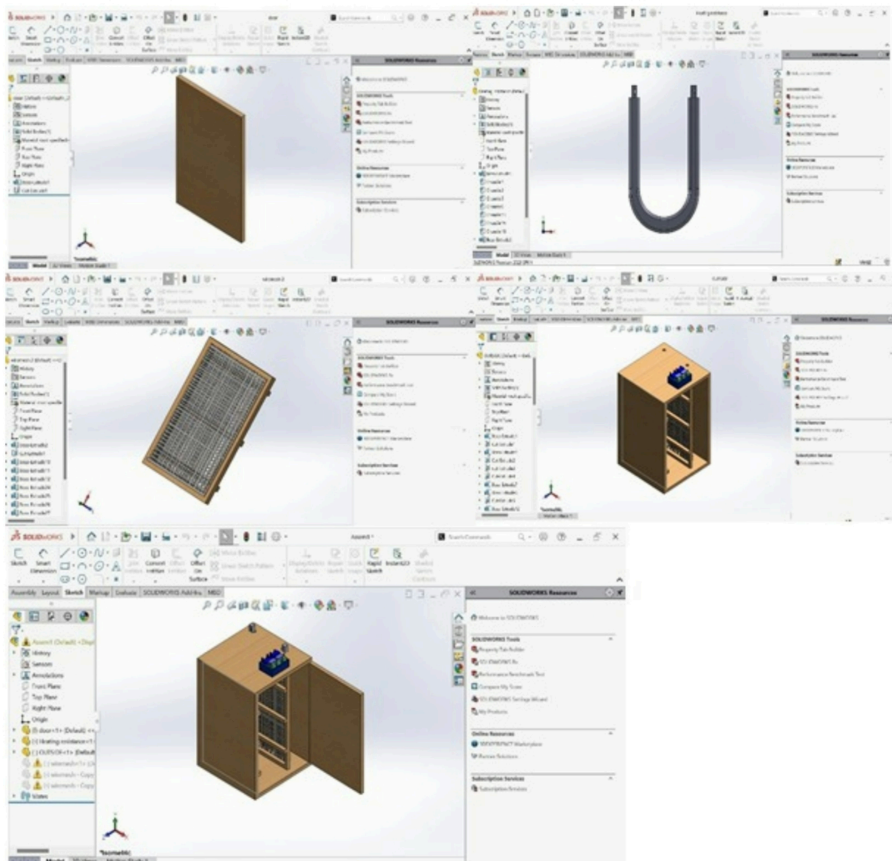


Figure 1

Three-dimensional model of the semi-automatic electric cabinet dryer produced in SolidWorks, showing the hinged door, stacked trays and the control module on top.

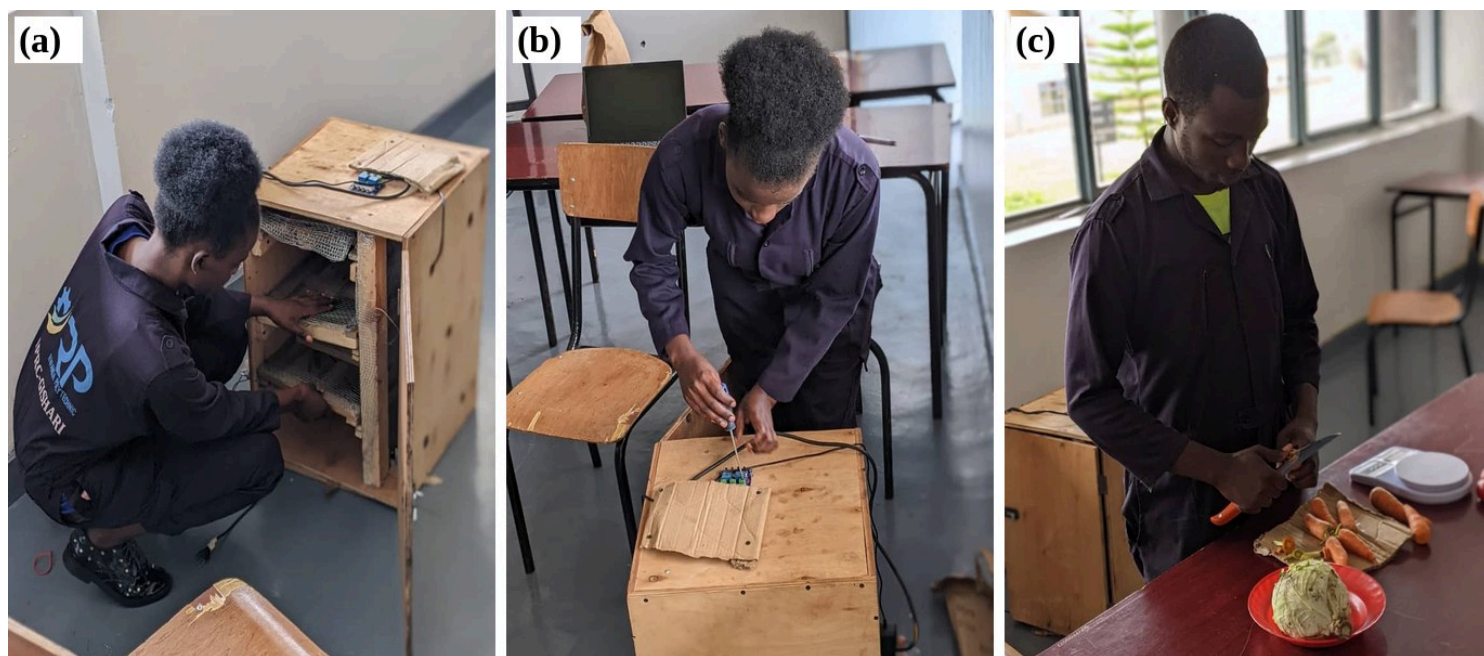


Figure 2

Fabrication and testing: (a) the prototype with wire-mesh trays and controller module; (b) wiring of the controller; (c) preparation and weighing of carrot, cabbage and tomato samples

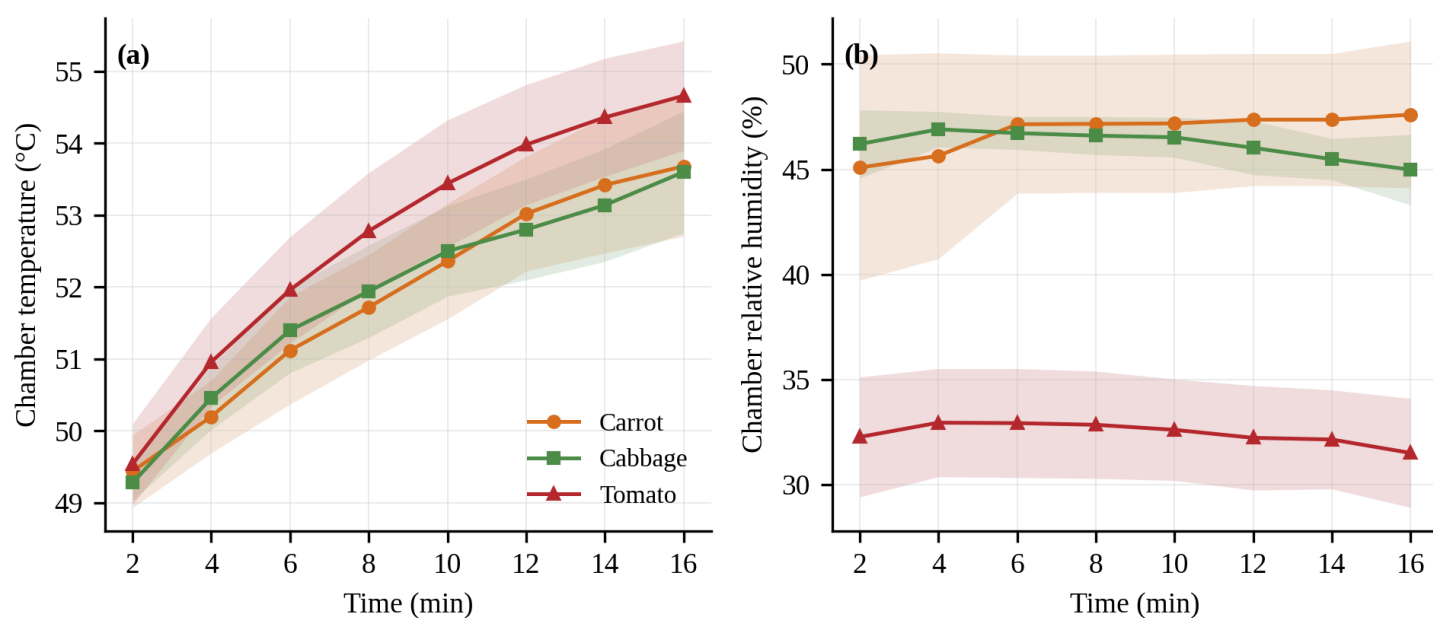


Figure 3

Chamber temperature (a) and relative humidity (b) during the 16-min runs. Symbols are means of five runs; shaded bands show ± 1 SD. Data are the two-minute sensor readings of the replicate sheets.

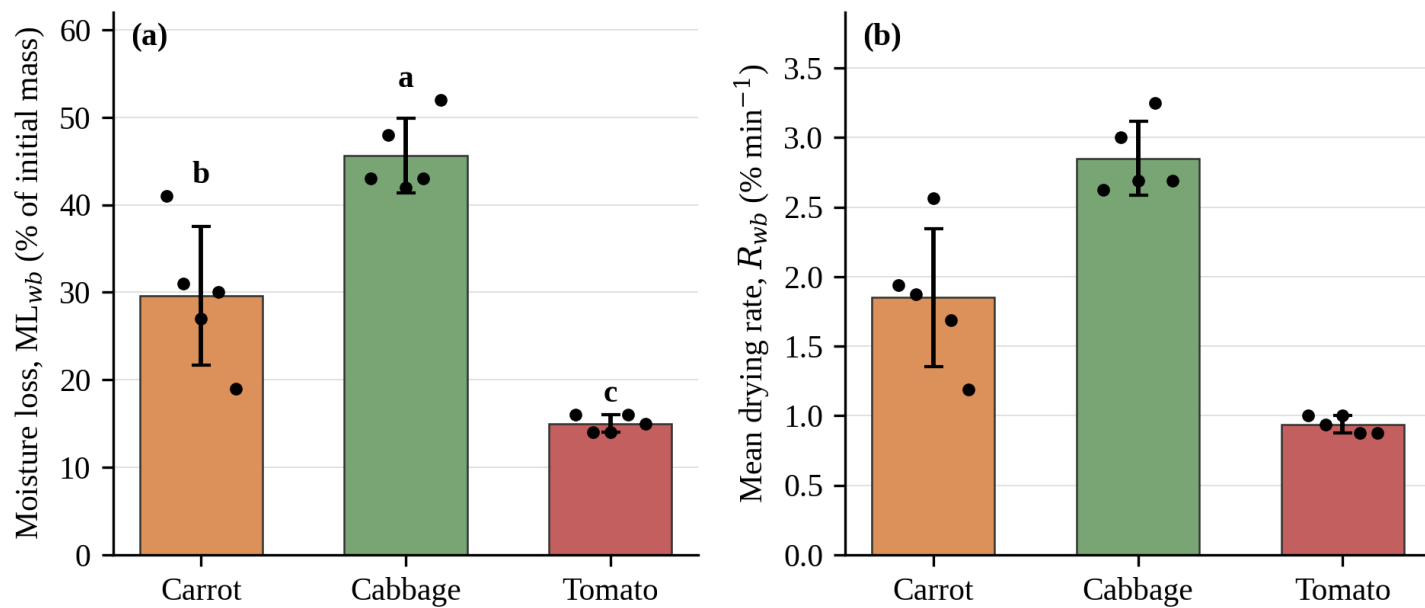


Figure 4

Moisture loss (a) and mean drying rate (b) on the initial-mass basis for the three crops. Bars are means, error bars ± 1 SD and dots individual runs ($n = 5$). Different letters in (a) denote significant differences (Games-Howell, $p < 0.05$).