Sustainable Food Technology

ROYAL SOCIETY OF CHEMISTRY

PAPER

View Article Online
View Journal

Cite this: DOI: 10.1039/d5fb00304k

Low-temperature low-humidity pretreatment followed by RF heating: a novel method of fig preservation

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Fig (*Ficus carica*) is an economic crop with significant health importance. Its post-harvest life is very short. Once dried, it is readily infested by insects. The aim of this study is to analyze whether low-temperature low-humidity (LTLH) drying followed by radiofrequency (RF) heating (for drying and disinfestation, respectively) is a treatment suitable for the food industry. During the preliminary study it was found that electrode heights of 180, 200, and 220 mm gave 100% mortality of *Oryzaephilus surinamensis* for all the time ranges studied. Hence, during the quality evaluation, these electrode heights and slow conveyor speeds (2.5, 5, and 7.5 m h^{-1}) were used. LTLH-dried figs served as a control, and further disinfestation of fig samples using RF heating (10 kW, 40.68 MHz) was performed. At 180 mm and 2.5 m h^{-1} (sample A), the moisture was most significantly reduced to 12.4%, which was much lower than that of the control (20.2%). However, the protein content fell significantly (by 31.17%), while the phenolic content (282 mg GAE per g) was significantly high after the treatment combination of 180 mm and 2.5 m h^{-1} (sample A). It was observed that the total phenolic content increased with increasing RF exposure intensity. The carbohydrate, fat, total dietary fiber, titratable acidity, total soluble solids (TSS), water activity, pH, and color values (L^*, a^*, b^*) of the treated figs showed no significant difference ($p > 0.05$) among the samples. Multi-criteria decision analysis (MCDA) found that sample B (180 mm and 5 m h^{-1}) ranked the highest (MCDA score = 0.62), with a higher normalized score of phenolic content, scavenging activity and moisture compared to the control (second-ranked MCDA score = 0.61). Thus, LTLH pretreatment followed by RF heating at an electrode height of 180 mm and conveyor speed of 5 m h^{-1} is suitable for quality retention.

Received 25th June 2025
Accepted 28th September 2025

DOI: 10.1039/d5fb00304k

rsc.li/susfoodtech

Sustainability spotlight

This study supports sustainable postharvest technologies for *Ficus carica* (fig), an economically and nutritionally significant crop with a short shelf-life and high vulnerability to insect infestation. The presented approach of integrating low-temperature low-humidity (LTLH) drying with radiofrequency (RF) heating ensures effective insect disinfestation (100% mortality) while retaining key nutritional and functional properties, such as phenolic content and antioxidant capacity. The optimized treatment (electrode height: 180 mm and conveyor speed: 5 m h^{-1}) strikes a balance between moisture reduction and nutrient preservation, offering an energy-efficient and chemical-free alternative for the food industry. This innovation aligns with UN Sustainable Development Goals, particularly SDG 2 – Zero Hunger by enhancing the shelf life and safety of nutrient-rich figs, SDG 3 – Good Health and Well-being through the preservation of antioxidants and bioactives, SDG 9 – Industry, Innovation, and Infrastructure by promoting sustainable processing technologies, and SDG 12 – Responsible Consumption and Production by reducing post-harvest losses and chemical use.

1. Introduction

Fig (*Ficus carica*; Moraceae) has been grown since 4000 B.C,[1] and is an economically important crop.[2] Turkey is the leading producer of figs,[3] followed by Egypt, Morocco, Greece, Iran, and Algeria; these six countries account for 70 percent of global annual fig production.[4] The common fig (*F. carica* L.) bears soft fragile fruits susceptible to fruit skin cracking and ostiole-end splitting during growth and development. A mature fresh fig has a pulp content of 84 percent and a skin content of 16 percent.[3] Fresh figs contain moisture (89.8%), protein (1.3%), fat (0.2%), minerals (0.6%), carbohydrates (17.1%), phosphorus (0.03%), iron (12 mg), and calcium (0.06%). They also contain 162 μg carotene, 60 μg thiamine, 50 μg riboflavin, and 600 μg niacin per 100 g.[5] Dried figs contain water (15.7%), reducing sugar (62.84%), protein (3.39%), ash (2.10%), total dietary fiber (5.80%), and acid (0.42%),[3] as well as various mineral

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compounds including potassium, calcium, magnesium, and sodium.[6] Because of the large amount of dietary fiber, vitamins, and minerals in dried figs, they have a better nutritional profile than any other dried fruit.[7]

Figs are also a source of a number of bioactive compounds. Vallejo and Marín[8] found that figs contain flavonols such as quercetin rutinoside, flavones like luteolin 6C-hexose-8C-pentose and apigenin-rutinoside, and phenolic acids such as chlorogenic acid. Various phenolic compounds are found in the peel, pulp, and leaves, including cyanidin 3-rutinoside, epicatechin, and caftaric acid, respectively.[9] The compound cyanidin-3-*O*-rutinoside has been found to contribute 92% of the total antioxidant capacity of the anthocyanin fraction in figs.[10]

Fig products have been used in traditional medicine to treat many diseases, mainly in the dermatological field.[11] It has been found that figs can be used as a dietary supplement and can contribute to various normal metabolic functions and growth. Specifically, their contents of essential amino acids, vitamins, minerals, dietary fiber and carbohydrates can be utilized in normal metabolic processes, and thus, they can be included as dietary supplements.[7] Figs also have several therapeutic effects, such as anticancer, hepatoprotective, hypoglycemic, hypolipidemic, antimutagenic, antispasmodic, and antimicrobial activities.[1]

Fresh figs are extremely susceptible to decay, and their post-harvest life is very short.[12] Thus, the choice of efficient packaging design methods is of great significance to the storage, transportation, and sale of figs.[13] Fresh figs are processed, dried, stored, and consumed as a dried fruit. During the storage of the dried fruit, losses mainly occur due to pests such as adult *Oryzaephilus surinamensis* L. and *Ephestia kuehniella* Zeller larvae.[14] The most common and abundant mite species found in stored dried figs include *Carpoglyphus lactis* (L), *Tyrophagus putrescentiae* (Schrank) and *Glycyphagus destructor* (Schrank).[15] The major storage pests of dried figs in Turkey and Greece have been reported to be *E. cautella* Walk., *Plodia interpunctella* Hbn. (Lepidoptera: Pyralidae), *O. surinamensis* L. (Coleoptera: Silvanidae), and *Carpophilus hemipterus* L. (Coleoptera: Nitidulidae), in decreasing order of importance.[16,17] Traditionally, fumigation was used to control these types of pest infestations, but it is avoided due to residue, health risks, and the potential for environmental pollution.[18] Scientists have attempted to use alternative techniques including ozone,[19] dielectric microwave treatment,[20–24] radiofrequency treatment,[25–29] controlled atmosphere storage[30] and modified atmosphere storage[31] on various food products. Combination treatments, like combined cold storage and microwave treatment,[32] have also been used for insect management of stored products. Among these, RF heating has attracted attention because of its rapid, volumetric heating and deeper penetration, which enable effective insect control without leaving toxic residues.[33] The exposure of various insects including *S. oryzae*, *Trogoderma granarium*, saw-toothed grain beetle (*O. surinamensis*), Indian-meal moth (*P. interpunctuella*) and the cigarette beetle (*Lasioderma serricorne*) to RF treatments has shown considerable mortality.[25] It has been reported that RF penetration depth decreases with increasing frequency and temperature, but this effect is on the order of tens of centimeters, making the development of industrial treatment systems for disinfestation possible.[33] Thus, it is clear that RF treatment can be used for insect disinfestation in various food products.

Low-temperature low-humidity (LTLH) drying is an emerging method to preserve the sensory and nutritional quality of figs, particularly sensitive compounds such as antioxidants. However, while LTLH drying ensures better quality retention compared to high-temperature methods, it does not provide protection against insect infestation during storage. Therefore, integrating LTLH drying with RF treatment offers a combined solution: LTLH for quality preservation and RF for safe, residue-free disinfestation. This dual approach directly addresses both nutritional quality and food safety challenges in fig processing. The present study was undertaken to evaluate the effectiveness of LTLH pretreatment followed by RF heating in achieving insect mortality while maintaining or improving the physicochemical and functional qualities of dried figs.

2 Materials and methods

2.1 Preparation of dried figs

Fresh figs of the Deanna variety were purchased from an orchard of the Namakkal district of Tamil Nadu, India. The figs were cleaned, washed and cut into round-shaped slices 1.5 ± 1.0 cm in thickness. The slices were treated with 0.2% KMS solution. A seed dryer (Make: Bry-Air (Asia); Model: FSD-600, 415 V, 50 Hz) was used to dry the figs under LTLH conditions. It was observed that the dried fig had a mean diameter of 31.28 ± 3.66 mm, a thickness of 4.77 ± 0.30 mm and weighed 3.79 ± 0.24 g. The slices were placed in the drying chamber and dried under set conditions of 30 °C and 10% R.H., until the moisture content stabilized to 20.2 ± 1.51% (w.b.). The figs were packed in an LDPE pouch and stored at ambient temperature until they were subjected to RF treatments.

2.2 RF heating

A 10 kW RF sterilizer (40.68 MHz; Make: Lakshmi Insta 10/4) was used to treat the LTLH-dried figs at different heights and for different durations. In this setup, an applicator with two flat-plate parallel rectangular electrodes was coupled to a generator. This was a 20 kVA air-cooled PLC-controlled system with a 25 kVA stabilizing capacity. The maximum and minimum product loading heights are 300 and 180 mm, respectively.

2.3 Preliminary study

A disinfestation study was conducted using different electrode heights (180, 200, 220, 260, 300 and 340 mm) to understand the lethal dose at which the RF heating can be deemed effective. The sawtooth grain beetle (*Oryzaephilus surinamensis* L.) is a dangerous insect that causes losses in dried figs.[14] Its life cycle involves various stages, including egg, larva, pupa and adult stages, and is completed within 30 days under ideal conditions. The adults are 2.4 to 3 mm in length, and they are long-lived, with lifespans of 6 to 10 months on average and some surviving up to 3 years. Adult sawtooth grain beetles were

Table 1 RF treatment combinations applied for mortality studies of *O. surinamensis*

Electrode height (mm)	Conveyor speed (m h^{-1})	Total treatment time (min)
180, 200, 220, 260, 300, 340	25	2.00
	22.5	2.05
	20	2.10
	17.5	2.20
	15	2.40
	12.5	3.00
	10	3.40
	7.5	5.00
	5	7.00
	2.5	15.00

cultured under laboratory conditions at 30 ± 1 °C and 60 ± 10% RH. The LTLH-dried figs (40.06 ± 1.01 g) were kept in a Petri plate of 100 × 15 mm and infested with ten uniform-aged adults for each treatment group and subjected to RF heating. Each RF heating treatment was performed separately and in triplicate. Different electrode speeds of 2.5, 5, 7.5, 10, 12.5, 15, 17.5, 20, 22.5, 25 m h^{-1} were also used for the study to provide different treatment times (Table 1). The treated plates were cooled for 24 hours and monitored to observe insect mortality. To confirm the death of an insect, it was gently rubbed with a brush to determine whether it was dead or simply pretending to be dead. The number of dead insects was noted.

2.4 Treatments for analyzing changes in quality parameters

The LTLH-dried figs were subjected to an extreme combination of RF treatments as deduced from a preliminary study (Fig. 1). Each treatment involved 40.96 ± 1.31 g of dried fig, and the studies were conducted in triplicate to reduce error. The voltage and current were held constant throughout the experiment at 5 V and 0.5 amperes, respectively. The initial and final air and product temperatures, along with the total time for each treatment, are summarized in Table 2. The anode current or the amount of current dissipated from the electrode was used to determine the intensity. The treated fig samples were cooled and stored in containers for further analysis.

2.5 Quality analysis

The dried figs were analyzed to determine their moisture, carbohydrate, fat, protein, ash, total dietary fiber, titratable acidity, reducing sugar, and ascorbic acid content, as well as the TSS, using methods described in the literature.[34,35]

2.5.1 Proximate composition. For estimation of the moisture content present in the fruit samples, the initial mass (m_1) of the fruit prior to LTLH was noted (30 g of fig), and after subsequent treatment the final mass (m_2) was measured. The moisture content (%) on a wet basis was estimated by using the formula $(m_1 - m_2)/m_2$ and multiplying the result by 100. However, the final values for carbohydrate, fat, protein, ash, and total dietary fiber content were converted to a dry basis for uniform comparison.

The total fat content of the fig samples after treatment was measured using a Soxhlet apparatus. The mass of the thimble (m_i) was measured. The sample (5 g) was ground and placed in the thimble, which was kept inside the boiling flask. Then, the flask was filled two-thirds of the way with solvent and boiled. The solvent used was *n*-hexane at a boiling temperature of 69 °C. The system was allowed to reflux and siphon for 6 hours. Then, the thimble was dried in a hot air oven at 105 °C for 60 min, and the final mass (m_f) was noted (AOAC 920.39). The fat content was calculated using the tabulated mass, $(m_f - m_i)/5$, and given in terms of percentage by multiplying the result by 100.

The total dietary fibre (%) present in the samples were estimated using a Fibra Plus automatic fiber extraction system (Pelican Equipment, Chennai, India, Model No-FES 2 R),[36] and the obtained values were tabulated using the mass balance as $(m_z - m_a)/m_z$ multiplied by 100, where m_z is the initial weight and m_a is final weight.

The sample (5 g) was placed in a crucible and incinerated inside a muffle furnace preheated to 550 °C. The final mass was measured along with the crucible. To determine the final mass of the sample (m_f), the initial weight was deducted and the ash content (%) was calculated using $m_f/5$ multiplied by 100 (AOAC 923.03).

The protein content of the fig was determined using a Kjeldahl apparatus (Pelican Equipment, Chennai, India, Model No-KES 06 VA DLS) following the standard procedures laid out by AOAC (984.13), and a numerical value of 6.25 was used as a conversion factor for the conversion of nitrogen. The sample (2 g) was mixed with sulfuric acid (15 mL), and 2 g of catalyst (potassium sulfate and copper sulfate, 10 : 1) was added. The sample was then digested by heating; the initial temperature was 350 °C, and the temperature was gradually increased until the sample became brown, black and then colorless. This was followed by distillation, in which 50 mL of NaOH (40%) was mixed with the digested sample and allowed to heat at 110 °C. The distilled liquids were trapped inside a conical flask containing 25 mL of a 2% boric acid solution until the conical flask was filled to 150 mL. A few drops of the mixed indicator (methyl red and bromocresol green) were added to the resultant solution inside the conical flask, and a burette was filled with 0.1 N HCl, which was used to titrate the solution in the flask until its color changed from green to pink. The following calculations were applied: nitrogen (%) = ((sample titre – blank titre) × normality of HCl × 14 × 100)/(weight of sample × 1000) and protein (%) = nitrogen (%) × 6.25. The carbohydrate content was calculated by difference.

2.5.2 Physicochemical analysis. The titratable acidity of the dried figs was measured by rehydrating the samples (5 g) in 100 mL of distilled water at 60 °C for 30 minutes, followed by filtration. An aliquot of the filtrate (25 mL) was titrated with standardized 0.1 N NaOH using phenolphthalein as an indicator, and the results were expressed as percentage of citric acid equivalent (AOAC 942.15).

The ascorbic acid content of the dried figs was measured by extracting 5 g of sample in 100 mL of 3% metaphosphoric acid, followed by filtration. An aliquot of the extract was titrated with standardized 2,6-dichlorophenolindophenol (DCPIP) solution

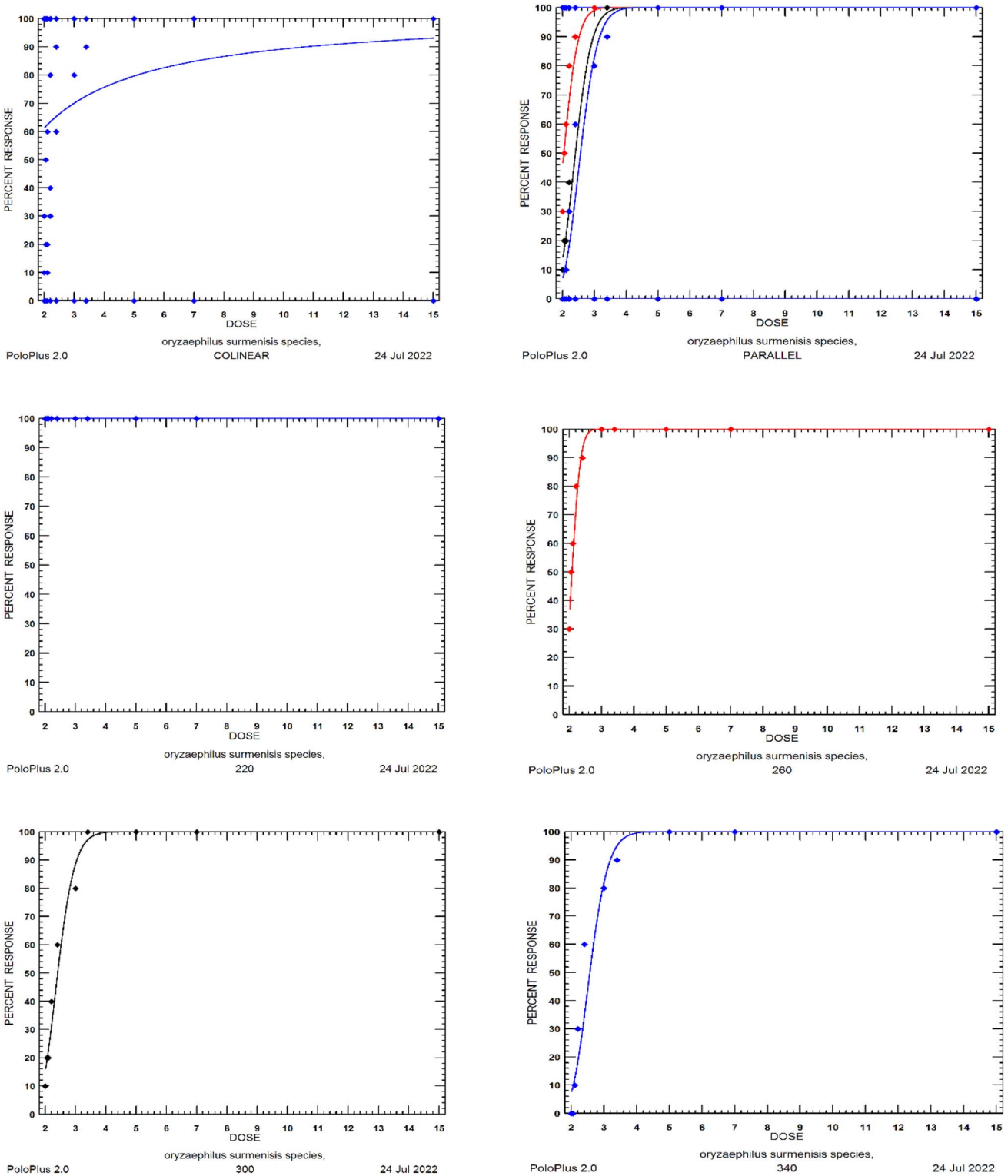

Fig. 1 Dose–response curves for radio-frequency-treated figs, showing the dose time (s) *vs.* the mortality of *O. surinamensis* adults (%).

until a light pink endpoint persisted for 15 seconds, as per AOAC Official Method 967.21. The results were expressed as milligrams of ascorbic acid per 100 grams of sample.

The total soluble solids (TSS) of the dried fig samples were measured by rehydrating 5 g of the sample in 100 mL of distilled water, followed by filtration. The TSS of the filtrate was determined using a digital refractometer at 20 °C and expressed as ° Brix.

The water activity of the samples was measured using a water activity meter (Aqua lab dew point, water activity meter 4TE).

Table 2 Comparative evaluation of physicochemical parameters after RF heating (mean ± SD)[a]

Sample	Electrode height (mm)	Conveyor speed (m h^{-1})	Initial product temperature (°C)	Final product temperature (°C)	Total treatment time (min)	Initial oven temperature (°C)	Final oven temperature (°C)
A	180	2.5	36.5 ± 0.36^{b}	95.7 ± 0.58^{a}	15	57.9 ± 0.20^{a}	59.6 ± 0.51^{a}
B		5.0	33.3 ± 0.20^{d}	90.7 ± 0.58^{b}	7	54.3 ± 0.20^{b}	55.8 ± 0.64^{b}
C		7.5	35.3 ± 0.15^{c}	84.7 ± 1.53^{c}	5	52.2 ± 0.05^{c}	54.3 ± 0.21^{c}
D	200	2.5	36.4 ± 0.10^{b}	90.0 ± 1.00^{b}	15	50.2 ± 0.11^{de}	52.4 ± 0.21^{d}
E		5.0	36.7 ± 0.15^{ab}	83.0 ± 1.00^{c}	7	50.6 ± 0.55^{d}	52.0 ± 0.11^{de}
F		7.5	36.3 ± 0.10^{b}	82.0 ± 1.00^{cd}	5	50.3 ± 1.32^{de}	52.5 ± 0.20^{d}
G	220	2.5	37.4 ± 0.30^{a}	90.7 ± 0.58^{b}	15	49.6 ± 0.23^{e}	51.2 ± 0.40^{ef}
H		5.0	36.2 ± 0.23^{b}	88.0 ± 1.00^{b}	7	50.1 ± 0.17^{de}	51.7 ± 0.20^{de}
I		7.5	36.3 ± 0.10^{b}	80.0 ± 1.00^{d}	5	49.6 ± 0.17^{e}	50.5 ± 0.00^{f}
J control		—	—	—	—	—	—

[a] Values with different letters in the same column differ significantly ($p < 0.05$).

The temperature during measurement was recorded and kept constant at 27 ± 1 °C. The pH of the samples was quantified using a pH meter (Horiba—PH1100, Model:9615S, Japan).

The total phenolic content of the fig samples was analyzed using the Folin–Ciocalteu method as described in ref. 37 using catechol standards. The absorbance was read at 760 nm using a UV spectrophotometer (Make: Shimadzu; Model: UV-1800) and expressed as mg gallic acid equivalents per 100 g of sample (mg GAE/100 g).

The antioxidant assay was performed using the DPPH method. A fig sample (1 g) was mixed in 20 mL of ethanol and vortexed thoroughly. The sample was allowed to rest for three hours and then made up to 30 mL with ethanol. The mixtures were centrifuged at 6000 rpm for 15 minutes, and the resulting supernatant was analyzed. For analysis, 2 mL aliquots of the supernatant were transferred to separate test tubes, and 2 mL of the DPPH reagent was added. The sample was vortex-mixed and incubated in the dark for 30 minutes. Finally, the absorbance was measured using a spectrophotometer at 517 nm.[38] The DPPH scavenging activity was calculated using the formula ((A1 − A2)/A1 × 100), where A1 is the absorbance of the control and A2 is the absorbance of the sample.

2.5.3 Color. The color of the dried figs was assessed using a colorimeter (Hunter Lab Color Flex EZ, Model: CFEZ0925, Hunter Associate Laboratory, Inc., Reston, Virginia, USA) by measuring opposite sides of the figs. The colorimeter had a 64 mm diameter viewing area and was calibrated using the standard black and white tile provided (X: 80.06, Y: 85.06, Z: 89.63). Measurements were recorded using the CIE color coordinates L^* (lightness to darkness), a^*, where $\pm a$ indicates greenness to redness, and b^*, where $\pm b$ indicates blueness to yellowness.

2.6 Multi-criteria decision analysis (MCDA)

This study was performed to rank the best sample based on the dependent variables using Minitab software. The analysis included seven parameters: two proximate composition parameters (moisture, protein, and ash), and five physicochemical characteristic values (reducing sugars, ascorbic acid, total phenolic content, and DPPH radical scavenging activity). However, the carbohydrate, fat, total dietary fiber, titratable acidity, TSS, a_W, pH, and color values (L^*, a^*, b^*) were not included, as they showed no significant differences ($p > 0.05$) among the samples studied.

All numerical data were compiled into a matrix, in which each row represented a sample (A–J) and each column had dependent variables. Only the mean values were used. To enable comparison across variables with different units and scales, min–max normalization was applied for each column on a scale of 0–1 using the formula given below in the Minitab calculator, and the values were expressed in a different column after normalization.

For benefit criteria (higher values are desirable):

$$\text{Normalized } x = (`x' - \min(`x'))/(\max(`x') - \min(`x'))$$

For cost criteria (lower values are desirable):

$$\text{Normalized } x = (\max(`x') - `x')/(\max(`x') - \min(`x'))$$

Where x = data of dependent variables.

The selection of benefit and cost criteria was based on the desired quality attributes. The following parameters were treated as benefit criteria (where higher values indicate better quality): carbohydrates, protein, ash, reducing sugar, ascorbic acid, phenolic content, and scavenging activity. The following were considered cost criteria (where lower values are preferred): moisture content. Then, equal weights were assigned to each normalized parameter, reflecting the assumption that all criteria are equally important for overall fig quality. The overall MCDA score for each sample was computed by taking the mean of the normalized values using row statistics. The samples were then ranked in descending order based on their MCDA scores to identify the most effective RF treatment in terms of overall quality retention. The MCDA approach was used in our study to integrate multiple quality parameters (*e.g.*, moisture, protein, ash, reducing sugars, ascorbic acid, and phenolic content, along with antioxidant activity) into a single ranking index.

Since no single parameter alone can comprehensively represent fig quality, MCDA acts as a tool that balances both benefit and cost criteria, thus enabling more reliable decision-making.[39]

2.7 Statistical analysis

The observed mortality data for *O. surinamensis* during RF treatments were subjected to probit analysis using Polo plus 2.0 (LeOra software, Petaluma, CA, USA) to determine the lethal time for 50% (LT_{50}) and 99.99% percent ($LT_{99.99}$) mortality.[40] The various physicochemical parameter data were statistically analyzed to find the significance of the results. These data were expressed as means ± standard deviations, and were compared with those of LTLH-dried fig (RF-untreated fig/control). One-way analysis of variance (ANOVA) was computed using Minitab (Version 17.3.1). The Tukey test was conducted at a 5% level of significance, and when $p < 0.05$, the data were considered significant. Further, MCDA was performed using calculator and row statistics in Minitab software.

3. Results and discussion

3.1 Preliminary study

The disinfestation procedure was carried out for dried figs infested with *O. surinamensis* adults at different electrode heights and times. A curve was plotted with the dose on the *X*-axis and the resultant response on the *Y*-axis. The resultant response is mortality, and the dose is the time corresponding to the mortality of the insect (Fig. 1). The probit analysis for an electrode height of 260 mm specified that the hypothesis of equality was accepted at $p < 0.05$ with an χ^2 value of 0.710. Similarly, for heights of 300 and 340 mm, the hypotheses of equality and parallelism were accepted with χ^2 values of 2.151 and 5.911, respectively. The disinfestation results indicated that an electrode height of 260 mm required the least time compared to heights of 300 and 340 mm, with an LT_{50} and $LT_{99.99}$ of 2.06 and 2.60 minutes, respectively (Table 3), while an electrode height of 340 mm required the longest time. This is due to the fact that mortality increases as the height of the electrode decreases, which was found to be in line with the observations of Jiao, Johnson *et al.*[41] and Tiwari, Shanmugasundaram *et al.*,[29] which had similar implications. It was observed that a 220 mm electrode height led to 100% mortality in a very short exposure time (Fig. 1). Similarly, the 180 and 200 mm electrode heights showed 100% mortality in all the time ranges studied. The longest time required to achieve mortality in this overall assay was found to be 3.80 minutes. RF is known to provide localized heating, first interacting more strongly with water than with dry matter.[42] It also provides homogeneity of heating, greater penetration depth, and more stable control of the product temperature. Hence, conveyor speeds of 2.5, 5, and 7.5 m h^{-1}, which correspond to treatment times of 15, 7, and 5 minutes, respectively, were considered for further studies, since this gave the highest intensity exposure. For the electrode height, the lowest heights were selected, *i.e.*, 220, 200 and 180 mm, as these give the highest intensity but may alter the quality of the LTLH-dried fig. LTLH pretreatment helps to reduce moisture level of fig; therefore, RF heating was utilized for the purpose of disinfestation only. If RF heating was used as the sole drying method as well as for disinfestation, the overall RF heating time would be increased, which might drastically affect the quality. Thus, this overall evaluation checks whether RF disinfestation of *O. surinamensis* reduces the quality of LTLH-dried fig.

3.2 Effect of RF disinfestation on various physicochemical parameters of dried fig

3.2.1 Moisture. The moisture content of the treated samples was found to be reduced significantly upon RF heating. This may be due to moisture leveling effects, and hence, RF heating of samples offers greater potential for even moisture distribution.[43] RF-treated figs were reported to have 17 to 23% moisture content by Hiwale;[3] the reduction in moisture content was found to be more pronounced in the current study (Table 4). However, at 180 mm electrode height the moisture content was reduced significantly. This may be due to LTLH drying, which was used as a pretreatment in the current study. Moisture loss has been reported even during ultrasound pretreatments of figs, which resulted in an enhancement in the end product quality as well as increased storability.[44] Similarly, moisture loss (92%) was reported upon microwave drying treatment of figs.[45] Samples A (12.4%) and B (15%) showed a significant reduction ($p < 0.05$) in moisture content compared to the control (LTLH-pretreated fig) because of the proximity of the sample to the electrode (Table 4). When the samples are closer to the electrodes, they will be exposed to higher-intensity radiofrequency waves;[29] the product temperature increased to 95.7 ± 0.58 and 90.7 ± 0.58 °C, respectively, favoring faster moisture removal. The moisture contents of the samples subjected to the majority of the other treatments did not exhibit a significant difference from that of the control due to the increased distance between sample and electrodes.

Table 3 Lethal time (min) to kill 50 or 99.99 percent of *O. surinamensis* adults exposed to radio frequency heating using various electrode heights[a]

Electrode height (mm)	LT_{50} (min) (lower–Upper limit)	LT_{99} (min) (lower–upper limit)	Slope ± SE	χ^2 (df)
260	2.06 (1.90–2.15)	2.60 (2.38–4.11)	23.14 ± 8.09	0.710 (8)
300	2.39 (2.25–2.60)	3.66 (3.15–5.24)	12.61 ± 2.75	2.151 (8)
340	2.55 (2.39–2.77)	3.80 (3.32–5.07)	13.40 ± 2.57	5.911 (8)

[a] Values are at the 95% level of confidence. df – degrees of freedom.

Table 4 Effect of RF treatment on the proximate constituents (mean ± SD) of dried figs.[a]

Sample	Moisture (%)	Carbohydrates (DWB)	Fat (DWB)	Protein (DWB)	Ash (DWB)	Total dietary fiber (DWB)
A	12.4 ± 0.25^{c}	60.1 ± 0.90^{a}	0.3 ± 0.25^{a}	11.5 ± 0.94^{bc}	6.3 ± 0.82^{abc}	14.1 ± 0.73^{a}
B	15.0 ± 1.07^{bc}	60.8 ± 1.33^{a}	0.4 ± 0.29^{a}	11.3 ± 1.12^{bc}	6.0 ± 0.19^{bc}	14.7 ± 0.62^{a}
C	16.5 ± 1.82^{abc}	60.4 ± 0.92^{a}	0.4 ± 0.11^{a}	11.0 ± 0.74^{c}	5.5 ± 0.29^{c}	14.3 ± 0.66^{a}
D	14.9 ± 1.61^{bc}	59.4 ± 1.13^{a}	0.6 ± 0.32^{a}	11.3 ± 0.66^{bc}	5.9 ± 0.34^{bc}	14.5 ± 0.41^{a}
E	17.1 ± 0.98^{ab}	60.1 ± 0.62^{a}	0.6 ± 0.40^{a}	10.6 ± 0.86^{c}	5.9 ± 0.16^{bc}	14.9 ± 0.48^{a}
F	17.3 ± 1.09^{ab}	61.1 ± 0.81^{a}	0.6 ± 0.36^{a}	11.1 ± 0.90^{c}	5.9 ± 0.08^{bc}	14.9 ± 2.13^{a}
G	15.8 ± 2.13^{abc}	60.5 ± 0.94^{a}	0.4 ± 0.30^{a}	12.5 ± 0.30^{bc}	6.6 ± 0.18^{ab}	14.2 ± 0.11^{a}
H	16.9 ± 2.53^{ab}	59.2 ± 1.12^{a}	0.5 ± 0.46^{a}	10.7 ± 0.73^{c}	5.9 ± 0.05^{bc}	15.1 ± 0.41^{a}
I	17.8 ± 1.28^{ab}	60.6 ± 1.51^{a}	0.3 ± 0.20^{a}	13.5 ± 0.63^{ab}	6.5 ± 0.19^{ab}	14.6 ± 1.01^{a}
J-control	20.2 ± 1.51^{a}	61.1 ± 1.22^{a}	0.7 ± 0.20^{a}	15.4 ± 0.90^{a}	7.0 ± 0.08^{a}	15.4 ± 0.94^{a}

[a] Values with different letters in the same column differ significantly ($p < 0.05$). Note: DWB means dry weight basis, expressed as g/100 g of dry matter.

3.2.2 Carbohydrates. The results of carbohydrate analysis showed that the carbohydrate contents of the treated samples were on par with that of the control. This means that the carbohydrate content did not change with the increase in temperature due to RF. The fresh figs had a carbohydrate content of 7.6%.[46] The LTLH-predried samples (control) showed a carbohydrate content of 61.1% on a dry basis (DB).

3.2.3 Fat. Figs naturally have a low fat content,[46] and it has also been reported that figs are fat and cholesterol-free.[10] No significant difference in fat content among the RF-treated and untreated fig samples was found (Table 4). This indicates that the LTLH drying and RF heating had no influence on the fat content of the figs.

3.2.4 Protein. The dried figs exposed to RF showed a reduction in protein levels for all the individual treatment combinations. The protein content of the control was on par with that of the sample treated using a 220 mm electrode height and 7.5 m h^{-1}. The samples treated using the specific treatment combinations of 180 mm and 7.5 m h^{-1}; 200 mm and 5 m h^{-1}; 200 mm and 7.5 m h^{-1}; and 220 mm and 5 m h^{-1} the showed the greatest significant reductions relative to the control (Table 4). RF dielectric heating of milk at temperatures ≥80 °C led to decreased whey protein nitrogen index and solubility, indicating protein denaturation and reduced solubility.[47] Under high-intensity RF exposure, amino acids may undergo Maillard reactions, deamination, or conversion into non-protein nitrogenous compounds.[48,49] Such compounds are less soluble and are not fully recovered during acid digestion/distillation, leading to an apparent reduction in measurable protein.[50] These changes suggest that high-temperature RF treatment can alter protein structures, potentially affecting nitrogen measurements. Studies on the RF heating of corn flour have shown that the surrounding media and electrode gaps influence the heating uniformity.[51] Uneven RF heating may have occurred in the LTLH-predried fig samples, causing localized overheating leading to quality deterioration, which may include protein degradation and nitrogen loss.

3.2.5 Ash. The ash content has been reported to increase upon the drying or dehydration of fresh figs.[3] In the present study, the RF treatment results showed that the ash content varied significantly from 5.5 to 7% in treated and untreated fig samples (Table 4). In contrast, radiofrequency treatment of milled rice samples using an electrode gap of 11 cm (110 mm) and 12.4 m h^{-1} showed no significant difference in ash content before and after treatment.[27] The differences in the RF treatment parameters could lead to variations in heating uniformity and intensity, potentially explaining the observed changes in the ash content.

3.2.6 Total dietary fiber. Fig naturally contains a combination of fiber and minerals.[52] Fig powder was found to be a rich source of fiber, with a dietary fiber content of 15.4%. The amount of total dietary fiber in the RF-treated samples was found to be on par with the control samples. The total dietary fiber content of the treated and untreated dried figs ranged from 14.1 to 15.4 percent (Table 4), which concurred with an earlier report by Hiwale.[3] The results revealed that RF treatments had no effect on the total dietary fiber content of dried figs.

3.2.7 Titratable acidity. The titratable acidity is directly related to the concentration of organic acids present in fruits.[53] The acidity of figs was found to be stable to drying and storage by Villalobos, Serradilla *et al.*,[44] while microwave-dried figs had much lower acidity.[54] The titratable acidity of the RF-treated and untreated figs was found to range from 0.3 to 0.8% citric acid (Table 5). A similar result was observed in ref. 55 for selected fig cultivars. The findings for the RF-treated and untreated figs indicated that RF had no significant influence on the acidity of the dried figs.

3.2.8 Reducing sugars. Glucose and fructose are the dominant sugars in fig fruits.[56] The sugars and organic acid content in fresh figs were found to be lower than those in dried figs.[57] The drying of figs leads to acid hydrolysis, Maillard reactions, and caramelization, which are the three major chemical events that affect sugars.[58] It was reported that the reducing sugar content increased during drying, which may be due to the conversion of non-reducing sugars to reducing sugars.[59] The results of the analysis showed that the reducing sugars contents in the fig samples ranged from 43 to 60% (Table 5). The RF-treated dried figs showed a significant decrease in reducing sugar content except for samples A and B.

Table 5 Effect of RF treatment on the physicochemical parameters (mean ± SD) of dried fig.[a]

Fig sample	Titrable acidity	Reducing sugar	Ascorbic acid	TSS (°Brix)	a_w	pH	Phenolic content	Scavenging activity (%)
A	0.3 ± 0.11^{a}	60.1 ± 0.58^{ab}	4.7 ± 0.37^{c}	37.1 ± 0.78^{a}	0.5 ± 0.06^{a}	5.4 ± 0.46^{a}	282.0 ± 6.56^{a}	92.4 ± 0.27^{c}
B	0.8 ± 0.52^{a}	60.3 ± 0.58^{ab}	5.2 ± 0.46^{a}	36.5 ± 1.14^{a}	0.6 ± 0.08^{a}	5.3 ± 0.24^{a}	224.3 ± 4.51^{b}	94.4 ± 0.70^{abc}
C	0.4 ± 0.28^{a}	44.3 ± 0.58^{e}	5.0 ± 0.42^{bc}	37.6 ± 1.71^{a}	0.6 ± 0.07^{a}	5.5 ± 0.21^{a}	205.7 ± 3.21^{c}	92.6 ± 0.81^{c}
D	0.8 ± 0.38^{a}	58.0 ± 1.00^{bc}	5.1 ± 0.39^{bc}	36.9 ± 1.01^{a}	0.6 ± 0.02^{a}	5.3 ± 0.24^{a}	174.3 ± 3.21^{e}	95.3 ± 0.73^{a}
E	0.6 ± 0.33^{a}	58.3 ± 0.58^{f}	5.1 ± 0.31^{ab}	37.8 ± 0.88^{a}	0.6 ± 0.07^{a}	5.4 ± 0.31^{a}	126.0 ± 2.00^{g}	94.9 ± 0.97^{ab}
F	0.7 ± 0.46^{a}	56.7 ± 1.16^{c}	5.0 ± 0.30^{bc}	37.2 ± 1.29^{a}	0.6 ± 0.01^{a}	5.6 ± 0.43^{a}	186.0 ± 3.00^{d}	93.8 ± 0.50^{abc}
G	0.6 ± 0.34^{a}	48.0 ± 1.73^{d}	4.7 ± 0.34^{c}	36.3 ± 0.96^{a}	0.6 ± 0.02^{a}	5.4 ± 0.32^{a}	195.7 ± 3.51^{cd}	93.7 ± 0.47^{abc}
H	0.6 ± 0.32^{a}	43.3 ± 0.58^{e}	5.1 ± 0.16^{bc}	37.7 ± 0.18^{a}	0.6 ± 0.09^{a}	5.3 ± 0.28^{a}	124.3 ± 2.52^{gh}	94.2 ± 0.76^{abc}
I	0.5 ± 0.36^{a}	43.7 ± 0.58^{e}	5.0 ± 0.29^{bc}	36.2 ± 1.97^{a}	0.6 ± 0.02^{a}	5.5 ± 0.16^{a}	151.7 ± 1.53^{f}	92.9 ± 0.83^{bc}
J-control	0.6 ± 0.38^{a}	60.4 ± 1.16^{a}	5.2 ± 0.09^{ab}	37.1 ± 1.23^{a}	0.6 ± 0.02^{a}	5.3 ± 0.25^{a}	115.7 ± 2.52^{h}	93.7 ± 0.86^{abc}

[a] Values with different letters in the same column differ significantly ($p < 0.05$).

3.2.9 Ascorbic acid. Vitamin C is susceptible to oxygen and heat, and can be damaged by oxidation even during drying under low-oxygen conditions.[60] The loss of ascorbic acid upon heat treatments such as drying or dehydration has been widely reported.[61–63] It was observed that samples A and G, which had conveyor speeds of 2.5 m h^{-1} (temperatures of 95.7 ± 0.58, 90.7 ± 0.58 °C, respectively) showed significant losses of ascorbic acid (Table 5). However, no significant difference was observed for the other combination RF treatments of figs. It is evident that RF treatment degrades the ascorbic acid content of dried figs only when they are exposed to a high intensity of RF for a long period.

3.2.10 TSS, water activity, pH. Total soluble solids (TSS) represent the content of soluble sugars, organic acids, and other minor constituents.[64] TSS have been reported to be increased upon the drying and storage of figs[55] which may be due to various metabolic process that convert carbohydrates into sugars, organic acids, and other soluble components.[65] The TSS of the RF-dried figs in the present study were in agreement with the findings of Villalobos, Serradilla *et al.*[44] The total soluble solids content of the RF-treated fig samples varied between 36 and 37 °Brix, and showed no significant difference from that of the untreated fig samples (Table 5).

Hot air, microwave drying, and controlled atmosphere treatment of figs have been found to result in significantly lower water activities below the optimum levels for microbial growth and toxin formation.[30,61,66] Similarly, a 27 MHz radiofrequency treatment of figs showed a reduced water activity of 0.7.[33] However, the water activity of the RF-treated samples in the present study showed variations between 0.5–0.6 at 27 ± 1 °C, with no significant variations from the control (Table 5).

It has been reported that the drying of figs decreased their pH significantly.[61] The present pH results indicated that the RF-treated fig samples showed no significant pH effect. Their pH values ranged from 5.3 to 5.6 (Table 5), which concurred with Villalobos and Serradilla *et al.*.[44] Therefore, it is evident that RF treatment had no effect on the TSS, a_w, and pH of dried figs.

3.2.11 Total phenolic content. In our study, radiofrequency (RF) treatment increased the total phenolic concentration of dried figs (Table 5). Sample A, which was exposed at 95.7 ± 0.58 °C (180 mm electrode height and 2.5 m h^{-1} conveyor speed), showed the most significant rise. This enhancement can be attributed to cell wall disruption during dielectric heating, facilitating the release of bound polyphenols, a phenomenon also reported in pitaya after RF treatment.[67] Figs are naturally an excellent source of phenolic compounds, and contain a higher concentration of total phenolics in the skin than the flesh.[8] The metabolic changes in phenolic compounds are linked with the activity of polyphenol oxidase, which is responsible for reactions impacting the quality of figs.[68] The total phenolics were retained better during the microwave drying of figs [45] and dried figs were found to have a higher phenolic content than fresh ones.[57] Konak and Kösoğlu *et al.*[55] reported that dark cultivars contained the highest levels of flavonoids and phenolics and exhibited higher antioxidant capacities than light-skinned cultivars. Fig wines were also found to have greater phenolic content and antioxidant capacity than normal fig juice.[69] Importantly, RF treatment did not negatively affect the overall phenolic profile of the dried figs, indicating that dielectric heating can be effectively integrated into post-harvest processing while preserving functional quality.

3.2.12 Antioxidant activity. Previous studies have reported that the antioxidant capacity of figs is highly correlated with their phenolic compound content[70] and anthocyanin content.[10,71] In comparison to fig pulp, the skins contribute the majority of the phytochemicals and antioxidant activity.[10] Upon the drying of figs, their antioxidant activity was found to increase (Slatnar *et al.*, 2011). Additionally, washing pre-treatments using peroxyacetic acid increased the antioxidant

Table 6 Effect of RF treatment on the color (mean ± SD) of dried figs.[a]

Sample	L^*	a^*	b^*
A	48.5 ± 3.13^{a}	11.1 ± 2.50^{a}	25.2 ± 5.46^{a}
B	40.1 ± 1.18^{a}	13.1 ± 1.10^{a}	25.9 ± 0.74^{a}
C	49.4 ± 1.96^{a}	11.6 ± 2.51^{a}	24.7 ± 3.67^{a}
D	41.5 ± 3.45^{a}	11.2 ± 3.37^{a}	26.3 ± 8.22^{a}
E	42.6 ± 3.83^{a}	13.3 ± 2.42^{a}	20.4 ± 5.62^{a}
F	49.8 ± 1.20^{a}	12.9 ± 1.26^{a}	26.8 ± 1.23^{a}
G	42.4 ± 6.03^{a}	11.6 ± 2.22^{a}	27.9 ± 7.77^{a}
H	49.4 ± 1.40^{a}	12.2 ± 1.73^{a}	24.2 ± 2.59^{a}
I	40.0 ± 0.99^{a}	11.7 ± 2.24^{a}	25.8 ± 1.84^{a}
J-control	46.4 ± 2.35^{a}	9.7 ± 1.16^{a}	20.0 ± 4.03^{a}

[a] Values with different letters in the same column differ significantly ($p < 0.05$).

Table 7 Normalization (Norm) of dependent variables and ranking using multi-criteria decision analysis (MCDA)

Sample	Norm moisture	Norm protein	Norm ash	Norm reducing sugar	Norm ascorbic acid	Norm phenolic content	Norm scavenging activity	MCDA score	Rank
A	1.00	0.19	0.53	0.98	0.00	1.00	0.00	0.52	4
B	0.67	0.15	0.33	0.99	1.00	0.65	0.69	0.62	1
C	0.47	0.08	0.00	0.06	0.60	0.54	0.07	0.35	10
D	0.68	0.15	0.27	0.86	0.80	0.35	1.00	0.55	3
E	0.40	0.00	0.27	0.88	0.80	0.06	0.86	0.50	5
F	0.37	0.10	0.27	0.78	0.60	0.42	0.48	0.51	6
G	0.56	0.39	0.73	0.27	0.00	0.48	0.45	0.42	7
H	0.42	0.02	0.27	0.00	0.80	0.05	0.62	0.36	9
I	0.31	0.60	0.67	0.02	0.60	0.22	0.17	0.38	8
J-control	0.00	1.00	1.00	1.00	1.00	0.00	0.45	0.61	2

activity of dried figs[72] The results of the present study showed that RF treatment had no significant effect of on the antioxidant activity of the dried figs (Table 5). Thus, the present results support the use of RF for disinfestation without any effect on antioxidant activity.

3.2.13 Color. Color is a crucial feature, because it is often the first thing a customer notices.[73] The heat treatment of food is linked to a change in hue. Food color retention following thermal processing can be used to forecast the degree to which food quality deteriorates as a result of heat exposure.[74] The results of the present study revealed that the L^*, a^*, and b^* values of the RF-treated samples exhibited no significant differences from those of the control (Table 6). However, a slight increase in L^* is noted due to the darkening of the figs. The maximum mean values of L^*, a^*, and b^* were 49.8, 13.3, and 27.9, respectively. This indicates that the RF treated samples had a similar color to that of untreated samples, and that the treatment showed good retention of the color of the dried figs.

3.3 MCDA analysis

Based on MCDA analysis, it was found that the control sample ranked second (MCDA: 0.61) in terms of quality, suggesting that RF treatment degrades the overall quality of the fig samples. However, the sample heated using a 180 mm electrode height and 5 m h^{-1} conveyor speed (sample B) ranked first (MCDA score: 0.62), with the highest normalized score for ascorbic acid (1.00) and higher phenolic content and scavenging activity compared to the control (Table 7). This sample also had significantly lower moisture content compared to the control (Table 4). This suggests that sample B has functional qualities with lower values of macronutrients (protein) compared to the control. The sample for which the lowest electrode height and fastest conveyor speed were used (sample C) ranked last (MCDA: 0.35), primarily due to its low normalized scores in protein, ash, reducing sugar, phenolics, scavenging activity, and moisture. This suggests that degradation of compounds occurred. Sample D showed the highest scavenging activity (1.00), but only moderate phenolic (0.35) and ascorbic acid (0.80) values, suggesting possible non-phenolic contributors to antioxidant capacity, such as Maillard reaction products. Ranking the samples clearly demonstrated the differences among the quality of the samples. The analysis also indicates that LTLH pretreatment to RF heating at a 180 mm electrode height and 5 m h^{-1} conveyor speed is suitable for quality retention, based on the different combinations studied.

4. Conclusions

The use of radiofrequency waves (10 kW, 40.68 MHz) to disinfest dried figs infested with *O. surinamensis* and their effect on various physicochemical parameters of the figs were discussed in the present study. The results of disinfestation indicated that an electrode height of 260 mm required the least time, with LT_{50} and $LT_{99.99}$ values of 2.06 and 2.60 minutes, respectively. Electrode heights of 300 and 340 mm required 2.39 and 3.66 minutes and 2.06 and 2.60 minutes to achieve LT_{50} and $LT_{99.9}$. The other three tested electrode heights of 180, 200, and 220 mm gave 100% mortality for all combinations of exposure time with different conveyor speeds.

The physicochemical parameters of the figs, such as carbohydrate, fat, ash, total dietary fiber, titratable acidity, TSS, pH, a_W, and color, were retained after RF treatment. The treatments not only maintained the antioxidant activity of the dried figs, but also increased the overall phenolic content. The exposure of dried figs to higher RF levels had a negative impact on protein and ascorbic acid, and lowered the reducing sugar content of the dried figs. All the characteristics investigated were within a commercially acceptable range. It was concluded that RF disinfestation can be utilized to disinfest dried figs without causing significant changes to their physicochemical properties.

Conflicts of interest

There are no conflicts to declare.

Data availability

All relevant data supporting the findings of this study are included in the article.

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