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Optimisation and influence of temperature and relative humidity on antioxidant capacity of mint leaves (*Mentha spicata* L.) during heat pump drying using response surface methodology

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Abstract

Chlorophyll, the primary pigment responsible for the green colour of mint leaves (*Mentha spicata* L.), is highly sensitive to degradation during intensive drying processes, leading to significant colour loss. To address this issue, mint leaves were dried using a heat pump dryer under varying conditions of temperature (40, 50, 60, and 70°C) and relative humidity (10, 20, 30, and 40%). The experiments were designed and analysed using the response surface methodology (RSM) to evaluate the impact of drying conditions on the quality attributes of mint leaves. Various nutritional and functional parameters, including antioxidant capacity, were assessed. The results indicated that drying at a low temperature of 40°C, and low relative humidity of 10% preserved the best overall quality, making the dried leaves suitable for use in powder production. Additionally, a gradual decrease in antioxidant capacity was observed with increasing relative humidity, decreasing from 2.32 mg/L at 10% humidity to 1.76 mg/L at 40% humidity. These findings highlighted the importance of optimising drying conditions to maintain the functional quality of mint leaves during processing.

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Introduction

Mint (*Mentha spicata* L.) is a member of the family Lamiaceae family. This annual and perennial herbaceous plants is farmed worldwide to take advantage of their special herbaceous qualities. According to Satyanarayana *et al.* (2001), the plant's green leaves are used to prepare iced tea, vinegar, jelly, and other foods and beverages. India uses mint extensively, and the states of Punjab, Himachal Pradesh, Haryana, Uttar Pradesh, and Bihar in the Southern Himalayas are the main locations for growing it. According to Adamiec and Kalemba (2006), the process of distilling freshly harvested peppermint leaves, or semi-dried, or dried leaves, yields peppermint essential oil suitable for commercial use. As an aromatic and medicinal herb, mint is primarily valued for its leaves, which are used in both traditional and complementary medicine. They can be used whole, ground, paste, or liquid. Mint leaves possess a variety of therapeutic properties, including diaphoretic, antiseptic, anti-asthmatic, antispasmodic, and stimulant effects. The leaves help in the treatment of cold, flu, fever, stomachache, food poisoning, rheumatism, hiccups, gas, and throat and sinus pains. It is also known to provide relief from nasal and throat ailments, infections, general fatigue, digestive issues, motion sickness, insect stings, skin irritations, and earaches (Arshad *et al*., 2023). Restaurants use mint powder as a flavouring and additive every day. It has flavour and scent due to the essential oils it contains (Özbek and Dadalı, 2007). Additionally, mint leaves are also used as perfume.

There are many ways to dry and store mint leaves: drying, freezing, and drying in the sun, *etc*. Freeze drying offers numerous advantages in terms of preserving the quality, nutritional value, and shelf life

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of heat-sensitive products. However, it comes with some disadvantages related to cost, time, and energy requirements for drying process (Kovac *et al.,* 2020). Solar drying works at a lower temperature than other drying methods, helping to preserve the nutrients in mint leaves. Inconsistent weather conditions can lead to variations in product quality, as it may be challenging to maintain consistent drying conditions (Muruganantham *et al.,* 2021). Shade drying method involves lower temperatures and slower drying, which can help preserve the flavour and essential oils of mint leaves, making them more suitable for culinary and medicinal purposes. It has limitations in terms of slower drying times, space requirements, and the potential for mould or spoilage if not managed properly (Ropelewska *et al.,* 2022). Electro-hydrodynamic drying (EHD) provides more uniform drying throughout the material, reducing the risk of over- or under-drying in different parts of the mint leaves. EHD is more energy-efficient than some traditional methods. However, it still requires electrical energy, which may not be entirely green if the electricity is generated from non-renewable sources (Esehaghbeygi and Karimi, 2020). Fluidised bed drying provides efficient and rapid drying due to the uniform and close contact between the hot air or gas and the mint leaves. This reduces drying time compared to other methods. However, in some cases, rapid drying in fluidised beds may cause the loss of some volatile compounds or essential oils in mint leaves (Beigi, 2019). Heating air dryer has comparative advantages such as independent fault control (temperature, humidity), high energy consumption, good drying, and no loss (Salehi, 2021).

Drying technologies are important in various industries, especially in food processing, textiles, and pharmaceuticals, where product quality and energy efficiency are paramount. Traditional drying methods, such as conventional dryers, often operate at high temperatures, leading to increased energy consumption and potential degradation of heat-sensitive materials. In contrast, heat pump drying technology has emerged as a superior alternative, offering several distinct advantages.

Heat pump dryers utilise a closed-loop system that recycles air, extracting moisture from products at lower temperatures. This method not only conserves energy—using up to 50% less energy compared to conventional dryers—but also preserves the integrity of heat-sensitive materials by preventing thermal degradation. Additionally, the absence of exhaust requirements in heat pump dryers allows for more flexible installation options, and reduces environmental impact. Given these benefits, heat pump drying technology presents a compelling solution for industries seeking efficient, gentle, and environmentally friendly drying methods. The present work discusses the principles, applications, and advancements of heat pump drying, underscoring its advantages over traditional drying techniques (Lee and Kim, 2009).

There are many studies on drying mint leaves with heat pumps, and examining the properties of mint leaves. Venkatachalam *et al.* (2020) observed a decrease from 83.45% (wt.) to less than 10% (wt.) in 6 h. The moisture diffusion mass of the air gap varied between 2.07534×10^{-11} and 3.45817×10^{-11} m^2/s. Ataei *et al.* (2015) studied the dehydrating of mint leaves at temperatures of 40, 50, and 60°C using a vibrating fluidised bed heat pump. Only at 40°C were colour measurements feasible; at 50°C, there was a slight but noticeable decrease in colour. Aktaş *et al.* (2017) investigated the characteristics of mint leaves that were dried in a dryer at 35°C with 2, 2.5, and 3 m/s. The water content of the leaf decreased from 9 to 0.1 g per gram of dry matter. The water diffusion rate of mint leaves varied between 3.5×10^{-11} and 5.88×10^{-11} m^2/s. PV/T drying auxiliary heating device (PVTAHPD) was designed and manufactured, and its heating, drying, and power supply capabilities were tested. When using the PVTAHPD method, mint leaves dried very quickly, and the average positive diffusion coefficient reached 4.69×10^{-11} and 3.70×10^{-11} m^2/s (Koşan *et al.,* 2020). In light of the aforementioned information, the purpose of the present work was to optimise the heat pump's process variables for drying mint leaves, and investigate how drying variables affect the leaves' quality attributes.

Materials and methods

i) Plant material

Fresh mint leaves were collected from Savina Mandi vegetable marketplace in Udaipur. Physiologically mature fresh green leaves were chosen for drying. Mint leaves were thoroughly washed under running tap water to remove dust, dirt, and foreign matter. After rinsing, leaves were blotted dry, and immediately dried. The temperatures of the dryer were 40, 50, 60, and 70°C, and the relative humidity were 10, 20, 30, and 40%. After drying, the samples dried under the most suitable conditions were selected for production. The initial moisture content of the samples was measured to be 84% (wet basis), and drying was continued until the samples reached a final moisture content of 6.27% (wet basis), which was considered the drying endpoint based on standard drying criteria for mint leaves.

ii) Process variables

Prior research has employed heat pump drying to ascertain a number of constants and variables in order to quantify the mint leaf shelf life. The goal of the initial trials was to determine the ideal drying temperature and relative humidity for products that are sensitive to heat. This was achieved by reading through a number of publications that covered the various combinations of temperature and humidity for various leaf types. On this basis, lower temperature and relative humidity, and the ability to dry and preserve food without dehumidification were selected (Sahoo *et al.,* 2012). Heat pump dryer consists of a drying chamber, air circulating unit, and heat pump. Heat pump drying has the ability to produce controlled transient drying conditions in terms of temperature, humidity, and air velocity to improve the product quality, and reduce the drying cost. It is a type of condenser dryer which extracts the heat energy from a source at low temperature (air outlet from the dryer), and makes it available as useful heat energy at higher temperature (drying air inlet). Therefore, the use of heat pumps makes drying applications more efficient and controllable. This technology is energy efficient and environmentally friendly than direct heated dryers.

Trials were also conducted to verify the effectiveness of drying behaviour of mint leaves with different relative humidity and temperature combinations. But due to the more chlorophyll content in leaves, it could not retain the colour properly. Therefore, there was a further need of controlling temperature and humidity in dryer to enhance the nutritional property of mint leaves. Trials were also conducted to verify the effectiveness of temperature, and the amount of moisture removal was different. Hence, on the basis of these facts, drying air temperature and relative humidity were considered separate process variables, and initial moisture (545.16% db.) was taken as constant parameter.

iii) Statistical analysis (experimental design)

The present work looked into how drying affected the kinetics and quality of drying mint leaves. The effects of relative humidity and drying time were investigated. The experiments were designed in Design Expert Software Stat Ease v 10 (trial version). Design quadratic model was used for two variables with four levels for each as shown in Table 1. The design contained a total of 16 runs (experiments). A numerical optimisation system was used in heat pump drying to optimise various input constraints such as drying temperature and relative humidity, and optimise the response; colour change, water activity, ascorbic acid, antioxidant capacity, rehydration rate, and water dispersion. When a design is I-optimal, the average prediction variance is reduced as shown below:

$$\text{Average variance} = \frac{\int f'(x)M-1\, f(x)dx}{\int dx}$$

The ability to loop through matrices when estimating the rows of the addition matrix to compute this average difference was utilised. It can therefore be rewritten as the mean estimated variation:

$$\text{Average variance} = \frac{1}{\int dx}\ .\ \text{tr}\ [M^{-1}B]$$

where, $B = \int f'(x)f(x)dx$.

Since χ is uniformly distributed throughout the experimental space, and its elements are proportional to time, this matrix is known as the time matrix. The test region was taken to be a (q - 1) dimensional simplex in its entirety.

iv) Colour variation

The colour of the dry sample was measured using a HunterLab colorimeter. Meanwhile the colour difference ΔE* was measured using the equivalent Hunter Scale (Karpagavalli *et al.,* 2014). A cylindrical glass sample (6.35 cm diameter × 4 cm depth) was inserted into the light port (3.175 cm diameter). The details are as follows:

Calibration procedure

Warm-up time

Before calibration, the colorimeter was allowed to warm up for at least 30 min to ensure sensor stability.

Table 1. I-optimal experimental design matrix using four different parameters.

Coded value of variable			Actual value of variable	
Exp. no.	X_1	X_2	Temperature (°C)	Relative humidity (%)
1.	1	-0.33	70	20
2.	-0.33	-0.33	50	20
3.	1	1	70	40
4.	0.33	-1	60	10
5.	1	-0.33	70	20
6.	-1	-0.33	40	20
7.	-0.33	0.33	50	30
8.	1	1	70	40
9.	-1	0.33	40	30
10.	-0.33	0.33	50	30
11.	1	-1	70	10
12.	-0.33	0.33	50	30
13.	-1	1	40	40
14.	0.33	-0.33	60	20
15.	0.33	-1	60	10
16.	-1	-1	40	10

White and black tile calibration
White calibration

The instrument was first calibrated using the certified white calibration tile provided by the manufacturer (L* = 100; a* = 0; and b* = 0, or as specified on the tile label).

Black calibration (if required):

Some models may require black trap calibration for zeroing reflectance.

The calibration tile was cleaned using a lint-free cloth to remove any dust or smudges before use. Calibration was performed through the instrument's built-in calibration menu, and values were adjusted automatically by the software to match the standard reference. The colour value of each sample was measured and repeated three times. The scale was initially measured using a black plate and a standard white plate. Hunter Laboratory colorimeters use the light index of the colour for colour purpose. Colour values L*, a*, and b* are components of the CIELAB colour space, and used to quantify colour characteristics. The L* value represents lightness, where +L* indicates a lighter colour and -L* a darker one. The a* value represents the red-green axis, with +a* indicating red, and -a* indicating green. The b* value corresponds to the yellow-blue axis, where +b* indicates yellow and -b* indicates blue.

Colour differences between fresh and dried mint leaves were calculated using the total colour difference (ΔE^*_{ab}) formula (Eq. 1):

$$\Delta E_{ab}^* = \sqrt{(L_2^* - L_1^*)^2 + (a_2^* - a_1^*)^2 + (b_2^* - b_1^*)^2} \quad \text{(Eq. 1)}$$

where, ΔE^*_{ab} = total colour difference between fresh and dried samples; L^*_1, a^*_1, b^*_1 = colour values of the dried sample; and L^*_2, a^*_2, b^*_2 = colour values of the fresh sample.

v) Water activity

Water activity (a_w) of the samples was measured using a LabSwift- water activity meter (Novasina AG, Switzerland). The formula of a_w is given by Eq. 2:

$$a_w = \frac{P}{P_0} \quad \text{(Eq. 2)}$$

where, a_w = water activity; P = vapour pressure of the substance at a specific temperature; and P_0 = vapour pressure of pure water at the same temperature.

Calibration procedure
Instrument warm-up

Prior to calibration, the a_w meter was powered on and allowed to equilibrate for at least 30 min to ensure thermal stability. This warm-up period minimises drift in the sensor readings.

Calibration standards

Calibration was performed using certified standard solutions or saturated salt solutions provided by the manufacturer. For example, standards with known a_w values (*e.g.*, a_w = 0.11, 0.33, 0.75, or 0.84 at 25°C) were used depending on the required measurement range.

Procedure

(1) Setup: insert the calibration cell into the instrument following the manufacturer's guidelines. (2) Measurement: initiate the calibration routine *via* the instrument's software or control panel. The meter will draw a measurement from the calibration solution, and the displayed value is compared to the certified value. (3) Adjustment: if any discrepancy is observed, the instrument is adjusted (*via* the internal calibration settings) to match the certified value. (4) Documentation: calibration data, including the reference standard values and the observed a_w values, are recorded for traceability and quality control purposes.

Measurement conditions

Temperature control

All measurements were conducted in a controlled laboratory environment, typically at 25°C, to maintain consistency since a_w is temperature dependent. If the instrument includes an internal temperature control feature, it was set according to the recommended operating conditions specified by the manufacturer.

Equilibration time

After the sample was loaded, the system was allowed an equilibration period (usually 20 - 30 min) to ensure that the sample's moisture equilibrated with the measurement chamber before reading the a_w value.

Environmental factors

Relative humidity in the testing area was monitored, especially when working in environments where fluctuations could impact the sensor. The instrument's measurement chamber is designed to minimise external air interference; however, it is recommended that measurements be performed in an area with low air flow.

Instrument settings and quality control

The instrument's software settings (*e.g.*, integration time and response time) were verified before each set of measurements. Repeated measurements (at least in triplicate) were performed on each sample to ensure reproducibility, and allow for statistical analysis of the data.

vi) Rehydration ratio

Rehydration rate was calculated as the ratio of the size of the rehydrated food and filter to the original product (Ranganna, 2017). Approximately, 5 g of dried sample was placed in 50 mL of 35°C distilled water in a 100-mL beaker, and heated in a hot water bath for 5 h. Then, the excess water and sample were removed. Tissue paper was used to absorb moisture before weighing. The rehydration rate of the dry sample was determined using Eq. 3:

$$\text{Rehydration ratio} = \frac{\text{Mass of rehydrated sample}}{\text{Initial mass of the sample}} \quad \text{(Eq. 3)}$$

vii) Ascorbic acid

The ascorbic acid content was obtained employing the technique outlined by AOAC (2019). Ascorbic acid is found in large quantities not only in citrus fruits, but also in vegetables. It is a water-soluble and heat-resistant vitamin. The ascorbic acid content (mg/100 g) in the sample was calculated using Eq. 4:

$$\text{Ascorbic acid} = \frac{0.5\ \text{mg} \times V_2\ \text{mL} \times 100\ \text{mL} \times 100}{V_1\ \text{mL} \times 5\ \text{mL} \times \text{wt.of sample (g)}} \quad \text{(Eq. 4)}$$

where, V_1 = amount of dye used in the reference solution (mL); and V_2 = amount of dye used in the test solution (mL).

vii) Antioxidant activity measurement

The 1,1-diphenyl-2-trinitrophenylhydrazine (DPPH) method was used to assess the free radical scavenging activity of mint leaf extract and conventional antioxidants (Thakur *et al.,* 2021). Peppermint leaf extract was prepared in methanol at various concentrations (50, 100, 300, and 500 parts per milligram). Standard antioxidants, such as butylated hydroxytoluene (BHT), were used at concentrations ranging from 1 to 100 µg/mL. Initially, 5 mL of 0.1 mM DPPH dissolved in methanol and 0.1 mL of standard solution were mixed. The extract's radical scavenging rate was computed using methanol (80%) and DPPH solution

(0.1 mM and 5 mL) as the blank and control samples. The mixture was shaken and incubated in the dark for 30 min. After that, incubation was performed for 30 min at 100°C using LED lights. The antioxidant activity was calculated using Eq. 5:

$$\text{\% Radial scavenging activity} = \frac{\text{Absorbance of control} - \text{Absorbance of sample}}{\text{Absorbance of control}} \times 100 \quad \text{(Eq. 5)}$$

ix) Moisture diffusivity

Diffusion coefficient is a measure of how much moisture moves out of a material during drying. During the slow drying phase, moisture changes occur due to molecular diffusion. The rate of diffusion is affected by material shrinkage, dry hardening of the surface, moisture content, and temperature. Assuming that moisture movement occurs by expansion, contraction, continual dissemination coefficient, and temperature, the solution to Fick's law was based on Darvishi *et al.* (2014):

Moisture ratio (MR)

$$M_R = \frac{M-M_e}{M_0-M_e} = \frac{8}{\pi^2}\sum_{n=0}^{\infty}\frac{1}{(2n+1)^2} exp\left[\frac{-(2n+1)^2\pi^2 D_{eff}t}{4H^2}\right] \quad \text{(Eq. 6)}$$

Eq. (6) when applied to extend drying times can be rewritten as follows:

Linearised form for diffusion

$$ln\left(\frac{M-M_e}{M_0-M_e}\right) = ln\frac{8}{\pi^2} - \left(\frac{\pi^2 D_{eff}t}{4H^2}\right) \quad \text{(Eq. 7)}$$

M_e can be ignored, and the moisture ratio can be stated in a more straightforward manner, because M_e is relatively little in contrast to M_o and M (Doymaz, 2004). Hence, Eq. 7 can be written as:

$$ln\left(\frac{M}{M0}\right) = ln\frac{8}{\pi^2} - \left(\frac{\pi^2 D_{eff}t}{4H^2}\right) \quad \text{(Eq. 8)}$$

where, M_R = moisture content, dimensionless; M = moisture content at any time, g H_2O/g dry matter; M_0 = initial moisture content, g H_2O/g dry matter; M_e = equilibrium moisture, g H_2O/g dry matter; D_{eff} = positive diffusivity, m^2/s; H = half thickness of the plate in the sample, m; n = positive integer; and t = time, seconds.

The semi-logarithmic form of Eq. (8) can be expressed as follows, using the general form:

$$ln(M_R) = A - Bt \quad \text{(Eq. 9)}$$

where, A and B= model constants, dimensionless.

The effective spread was calculated from experimental drying data, usually expressed as ln (MR) versus drying time. Eq. 9 shows that ln (MR) is a function of drying time and slopes in a straight line.

$$Slope = \frac{\pi^2 D_{eff}}{4H^2}$$

Results and discussion

Process parameter optimisation to extend mint leaf shelf life

Using the statistical programme Design-Expert 10.0.1, the processing parameters—temperature (°C) and relative humidity (%) were mathematically optimised. All the responses (colour variation, water activity, ascorbic acid, antioxidant capacity, rehydration ratio, and moisture diffusivity) were considered for optimisation. The goals were maximising the responses and adjusting essentials to increase the shelf life of mint leaves.

The optimisation was done using solution with the highest desirability (0.698) from a set of 16 solutions. Table 2 displays the most optimal point that was attained. It demonstrates that freshly harvested mint can be stored safely after heat pump drying.

Table 2. Optimisation of process parameters for HPD of mint leaves.

Parameter	Optimum value
Temperature (°C)	40
Relative humidity (%)	10
Rehydration ratio	5.44
Ascorbic acid (mg/100 g)	11.63
Water activity	0.264
Colour variation	9.86
Antioxidant capacity (mg/L)	2.18
Moisture diffusivity (m^2/s)	1.14

Development of mint powder through process parameter optimisation

Mint leaves were dried using heat pump dryer (HPD) at temperature of 40, 50, 60, and 70°C, and relative humidity of 10, 20, 30, and 40%. After drying, the samples dried under the most suitable conditions were selected for powder production. Due to its low energy consumption, low loss, high thermal performance, and drying performance, HPD is used more in the food industry. The reverse Carnot cycle, also known as the cooling cycle, is the basis for energy savings in drying. It has the ability to recover energy from exhaust gases, and independently regulate air temperature and humidity (Deng *et al.,* 2015; Aguirre-Alonso *et al.,* 2019). When drying mint leaves with a heat pump, colour indices were very close to each other at temperatures between 40 and 50°C, while a significant loss of green colour was observed when the temperature increased to 60°C (Ataei *et al.,* 2015). A previous study observed dried melon slices using a dryer, and process input variables included drying temperature (35 - 45°C), speed (0.5 - 1.0 m/s), and slice thickness ranging from 5 - 9 mm. Utilising the response surface method (RSM), one can assess how independent variables have an impact such as temperature (°C), slice thickness (mm), and drying speed (m/s) on variables such as drying time (min) and total energy consumption. Mint leaves were eventually dried and ground into powder (Figure 1), and this powder contained all the ingredients needed to make the product.

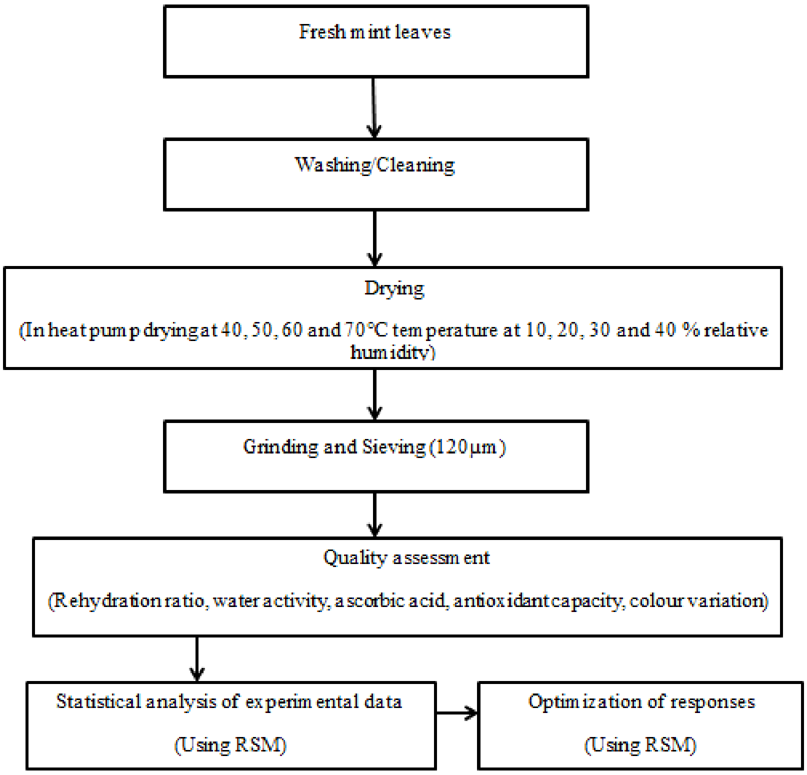


Figure 1. Flowchart of experimental work plan.

Effect of variables on dried mint leaves' composition

Colour variation of dried samples

The effects of various functions such as temperature and humidity on colour change (Figure 2) were analysed using design expert software version 10.0.1. Independent parameter values (temperature and relative humidity) of mint leaf colour values after drying with a heat pump were calculated using Eq. 10. The colour change pattern was significant (p < 0.01), and temperature and humidity had significant (p < 0.05) effect on colour change at both linear and quadratic levels. Regression tests were also performed to match the functional response or colour change of dried mint leaves. The increase in R^2 and R^2 adj confirmed the validity and accuracy of the model by showing how good the test and prediction results were.

Colour variation =

$$9.512-0.062A-0.015B+0.00073AB+0.0014A^2 \quad \text{(Eq. 10)}$$

Figure 2. Heat pump dried mint powder with optimum condition of temperature and relative humidity.

A graphic analysis was also conducted to examine the impact of temperature and relative humidity on the colour change of dried mint leaves (Figure 3). The figure makes it evident that as temperature increased from 40 to 70°C, the colour variation increased from 9.51 to 12.71. The change in colour (ΔE) value of 10% humidity and 40°C drying air temperature (9.508) was lowest, and 40% humidity and 70°C drying air temperature was highest (13.64). When the percent relative humidity was increased from 10 to 40%, the ΔE value increased from 12.71 to 13.64 for mint leaves. A previous study

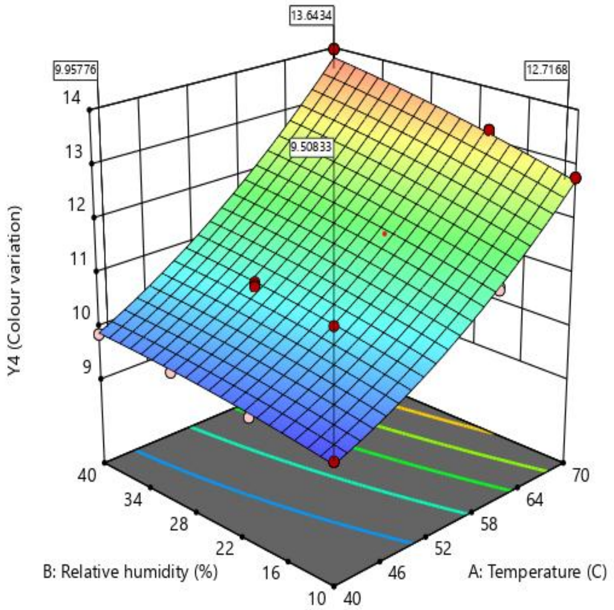


Figure 3. Combined effect of temperature and relative humidity on high-level colour change of dried mint leaves at optimum level.

also found similar results when drying mint leaves. In other words, the higher the relative humidity, the higher the air humidity around the leaves. This prolongs drying time, and increases the period of enzyme activity in the leaves. In particular, the enzymatic browning reaction darkens the colour and appearance of dried mint leaves. The colour of the product is an important factor that must be protected during onion drying. More colour change was observed at a lower temperature of 35°C, probably due to the 840 min drying time. However, the colour changes of the samples dried at different temperatures in the dryer did not change much. Samples dried in a dryer at 50°C were found to have better colours compared to samples dried with hot air, probably due to the drying time in the HPD (Sahoo *et al*., 2012).

Antioxidant capacity of dried samples

The properties of mint leave help reduce the production of free radicals in the body. Mint contains bioactive compounds that have shown antioxidant and potential anticancer activities in preclinical studies, which may contribute to health-promoting effects when included as part of a balanced diet. The activity that eliminated radicals that were free of fresh mint leaves on the day of harvest was 8.75%. Activity that eliminated radicals that were free of mint samples decreased when dried at 40°C and 10% relative humidity, and when dried at 70°C and 40% relative humidity.

Analysis of variance showed a significant increase in free radical scavenging ($p < 0.01$). The table also shows that temperature and relative humidity have significant effect of 1% on the activity that eliminated radicals that were free of dry leaves ($p < 0.01$). Based on statistical analysis, the proposed model was reasonable and appropriate. Experiments have also been conducted to treat the chemical reaction or the dried leaves' ability to scavenge free radicals. The increase in R^2 and R^2 adj confirmed the effectiveness and accuracy of the model by showing how good the testing and prediction were. The non-significant ($p > 0.05$) lack of fit further increased the consistency of the model as shown in Eq. 11:

$$\text{Antioxidant capacity} = 4.079 - 0.037A - 0.0354B + 0.00035AB \quad \text{(Eq. 11)}$$

The effect of temperature on the antioxidant capacity of mint leaves is shown in Figure 4. The figure shows that the antioxidant capacity of the dried sample increased by up to 73% as the drying temperature increased from 40 to 70°C, suggesting an optimal temperature range for preserving antioxidant activity. However, further increases beyond this point resulted in degradation of bioactive compounds, as discussed later. The antioxidant capacity of mint leaves can be affected by many factors, including dry air. Antioxidants are compounds that help protect cells from damage caused by free radicals, which are reactive molecules that can cause oxidative stress and a variety of health problems. Drying temperature may cause loss of antioxidant properties or decrease effectiveness (Ataei *et al.,* 2015). Figure 4 shows the effect of temperature on the antioxidant capacity of mint leaves. As the relative humidity of mint leaves increased from 10 to 40%, the antioxidant capacity of the dry sample also gradually increased from 35%. This may be because relative humidity increases the risk of oxidation in dry mint leaves. Oxidation causes antioxidants to break down, and their effectiveness decreases.

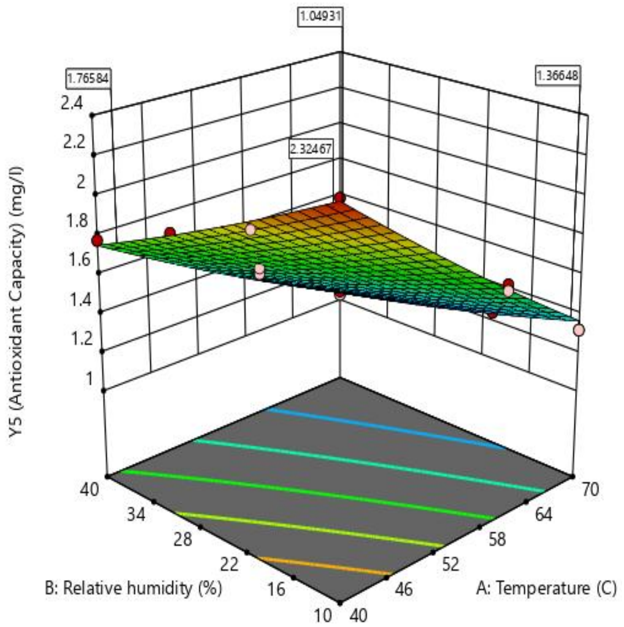


Figure 4. Combined effect of temperature and relative humidity on antioxidant capacity of dried mint leaves at optimum level.

Further, at low level of temperature (40°C), when relative humidity of drying chamber was increased from 10 to 40%, there was a gradual decrease in the antioxidant capacity from 2.32 to 1.76 mg/L. But at high level of drying temperature (70°C), there was a sharp decrease in the antioxidant capacity from 1.36 to 1.04 mg/L, as relative humidity of drying chamber was increased from 10 to 40%. Similarly, when relative humidity was kept at low level (10%), antioxidant capacity of the sample was decreased from 2.32 to 1.36 mg/L, with increase in temperature (40 to 70°C). This much decrease in antioxidant capacity might result from the fact that higher temperatures during drying can lead to the degradation of some heat-sensitive antioxidants, whereas at high level of relative humidity (40%), antioxidant capacity was decreased from 1.76 to 1.04 mg/L with increase in the temperature from 40 to 70°C. Leaves were dried at different temperatures, 40 to 70°C. During the observation, lower temperature dried mint leaves showed lesser antioxidant loss as compared to higher temperature and higher humidity.

Water activity of dried samples

Fresh mint leaves were found to have very high a_w (0.890). a_w sharply decreased as the product lost moisture during the drying process, 0.264 a_w at 40°C and 10% relative humidity. a_w for 10% set humidity and higher temperature was less. When the percent humidity was increased from 20% to 30 and 40%, the a_w increased. When mint leaves were subjected to higher drying temperatures, the increased thermal energy promoted faster moisture evaporation from the leaves. This rapid moisture removal reduced the amount of a_w in the leaves (Mohanty *et al.,* 2021). The a_w model was found to be highly significant ($p < 0.01$). Dry air temperature had significant effect on a_w of dry leaves ($p < 0.01$) as shown in Eq. 12:

Water activity =
$$0.278-0.00048A+0.0016B-0.000017AB \qquad \text{(Eq. 12)}$$

Figure 5 shows the influence of dry air on the a_w of dried mint leaves. It can be seen from the figure that a_w decreased by 3.22% when dry air increased from 40 to 70°C. When mint leaves were subjected to higher drying temperatures, the increased thermal energy promoted faster moisture evaporation from the leaves (Potisate *et al.,* 2014).

The a_w of dehydrated mint leaves increased linearly and progressively by 2.73% as the relative humidity of the leaves increased from 10 to 40%. This may also have to do with the fact that dried leaves had higher a_w when the surrounding environment's relative humidity increased. Figure 5 shows the combination of temperature and relative humidity. The outcomes indicated that a_w of dried mint leaves decreased by 7.14% when the temperature decreased from 40 to 70°C. The moisture content of dried mint leaves increased by 9.77%. Moreover, Figure 5 shows that at high relative humidity (40%), the a_w gradually decreased from 0.292 to 0.263 when the dry air in the drying room increased from 40 to 70°C. However, when the relative humidity of the high temperature (70°C) drying room increased from 10 to 40%, a_w (6.47%) increased.

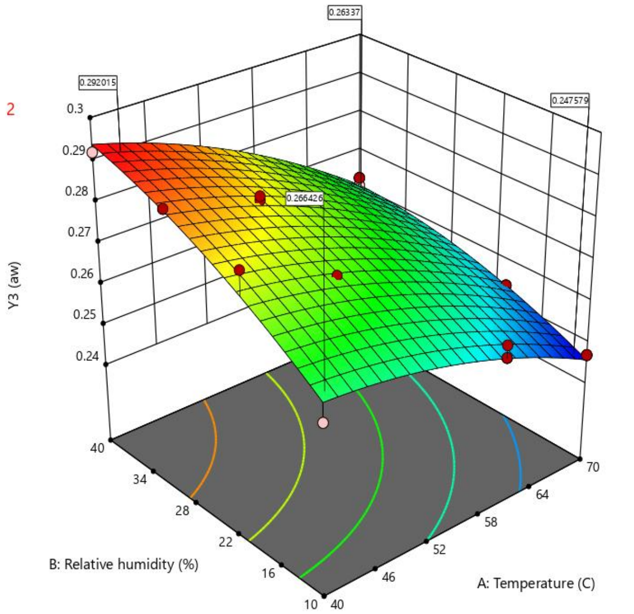


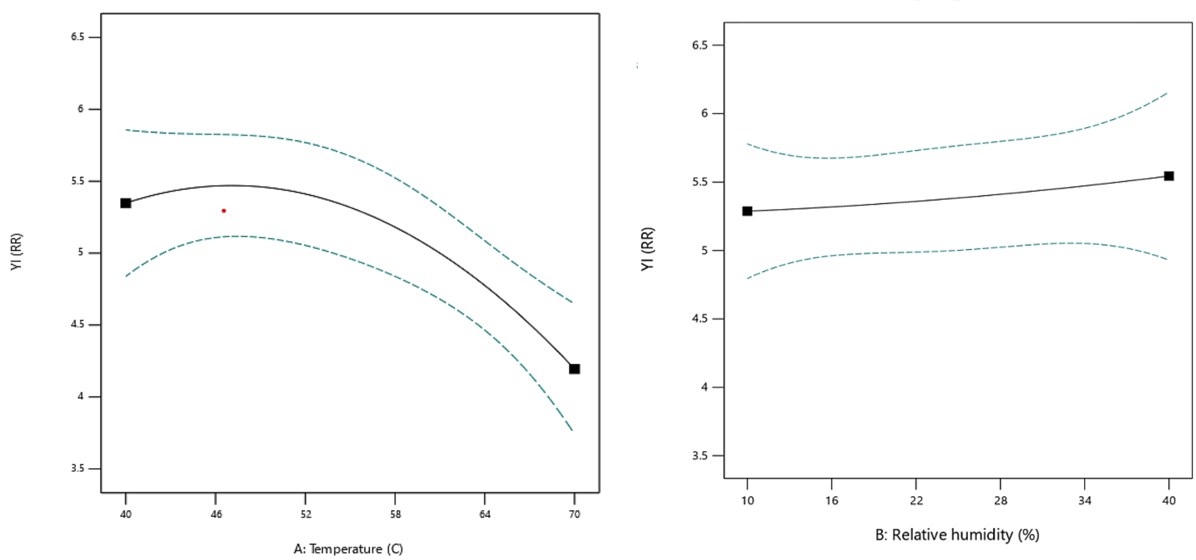
Figure 5. Combined effect of temperature and relative humidity on water activity of dried mint leaves at optimum level.

Rehydration ratio of dried samples

To evaluate the effect of different parameters on the drying of mint leaves, experimental data were recorded in a drying chamber at 40°C and 10% relative humidity. The independent variable temperature (X_1) had significant effect on the rehydration of the outflow line ($p < 0.01$), but the four levels or interaction did not ($p > 0.05$). Regression analysis was also performed to fit the dry mint leaf rehydration rate. The increase in R^2 and R^2 adj confirmed the validity and accuracy of the model by showing how good the test and prediction results were. The non-significant ($p > 0.05$) lack of fit further demonstrated the validity and reliability of the model. To represent the relationship between values of each process variable, a quadratic model was fitted by selecting only key process variables with actual values (Eq. 13):

Rehydration rate = 0.825+0.201A-0.0021B (Eq. 13)

The results were significant at the 1% level ($p < 0.01$). The rehydration ratio suddenly increased linearly by 22.38% when the dry air temperature increased from 40 to 70°C. The rehydration ratio increased with increasing air temperature for drying, probably because drying at higher temperatures led to lower moisture content, which in turn increased water content during rehydration. Supakarn *et al.* (2018) found similar results. In addition, Figure 6 shows the effect of rehydration ratio of mint leaves on the appearance of dry air and relative humidity. As the relative humidity in the dry room increased from 10 to 40%, the rehydration ratio of dry mint leaves increased linearly and gradually by 24.03%.



(A) **(B)**

Figure 6. Effect of dry air and humidity on mint leaf rehydration rate under different processing conditions.

Ascorbic acid of dried samples

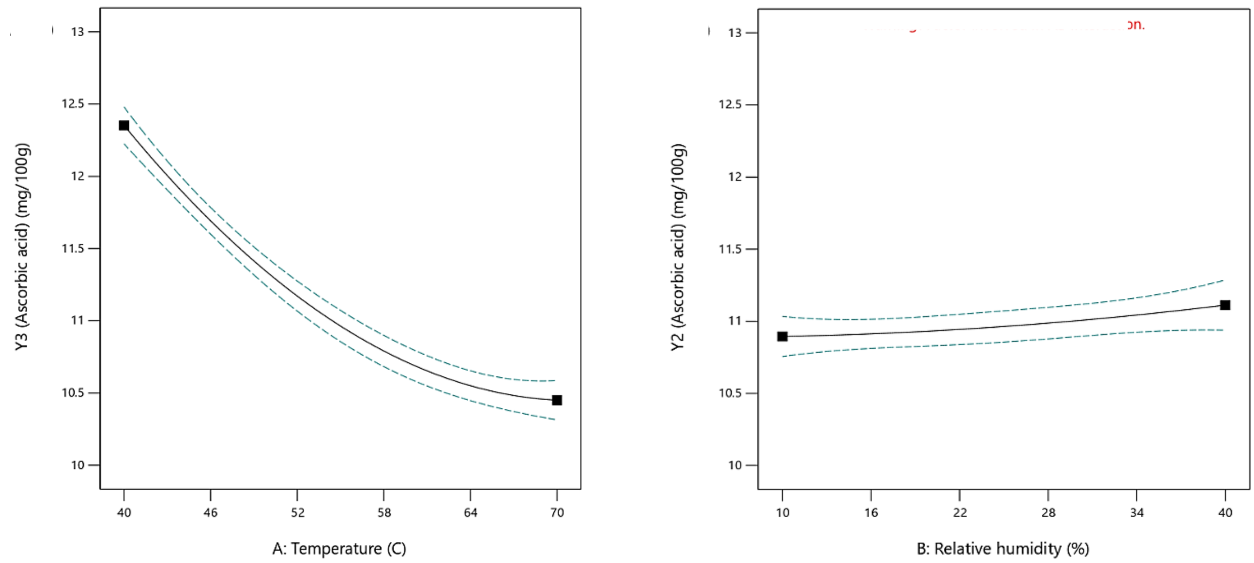
As shown in Figure 7, the vitamin C content of dehydrated mint was lesser at higher temperatures. Experimental data were analysed to evaluate the main influence of various parameters on the ascorbic acid content of mint leaves dried and stored in a drying chamber at 40°C and 10% relative humidity. Figure 7 shows the significant outcome of temperature and humidity on the ascorbic acid content of dried mint leaves and prepared samples ($p < 0.01$). Figure 7 clearly shows that ascorbic acid content is significantly affected by the change of temperature (X_1) and relative humidity (X_2) at the linear level ($p <$ 0.01), but not at the four levels or interaction ($p >$ 0.05). Statistical analysis confirmed the validity of the proposed model. A recovery test was also conducted for the ascorbic acid activity content of dried mint leaves. The increase in R^2 and R^2 adj confirmed the validity and accuracy of the model by showing how good the test and prediction results were. The absence of a notable mismatch ($p > 0.05$) also indicated the validity and reliability of the model. The relationship between ascorbic acid content in mint leaves and process variables was represented by fitting a quadratic model (Eq. 14) using only the main process variables and actual results:

$$\text{Ascorbic acid} = 20.24-0.279A+0.0065B+0.0019A^2 \quad \text{(Eq. 14)}$$

Figure 7 shows that ascorbic acid content increases linearly by 1.55% when the dry air temperature decreases from 70 to 40°C. This indicated that dried mint leaves with higher drying air temperature showed the lowest ascorbic acid content. The ascorbic acid content increased with increasing dry air, probably because when the leaves were exposed to heat, the ascorbic acid present in the leaves reacted with oxygen, leading to the formation of dehydroascorbic acid, oxidised form of ascorbic acid, and decreased ascorbic acid content in leaves. Similar results were obtained on mint leaves by Colak *et al.* (2008). Additionally, Figure 7 shows the effect of ascorbic acid content in mint leaves on dry air and relative humidity. The increase in humidity from 10 to 40% gradually decreased the 2.78% ascorbic acid content in dry mint leaves. This can be due to the fact that drying time can be slowed down by increasing humidity. Therefore, the leaves burned for a long time, which could lead to partial degradation of ascorbic acid due to its thermal sensitivity.

Moisture diffusivity of dried sample

In drying, diffusivity is used to specify the movement of moisture through the material. The diffusion rate is affected by material shrinkage, surface hardening during drying, moisture content, and temperature. From the experimental results, it was found that the moisture diffusivity of dried mint increased with increasing temperature. Specifically, as the drying air temperature increased from 40 to 70°C, moisture diffusion increased linearly by 15.29%. In order to evaluate the main effect of variables such as temperature and humidity on the



(A) **(B)**

Figure 7. Effect of drying temperature and humidity on ascorbic acid content in mint leaves under different temperature and relative humidity conditions.

distribution of dried mint leaves, experimental data were recorded and analysed in a drying chamber at 40°C and 10% relative humidity. Analysis of variance showed that the water diffusivity pattern was significant ($p < 0.01$), and temperature and relative humidity had significant effect on the water diffusivity of dry mint leaves. The temperature (X_1) and humidity (X_2) as independent variables had significant effect on leaf water dissipation ($p < 0.01$), but there was no significant effect on the four levels or interactions ($p > 0.05$). The absence of any other non-significant ($p > 0.05$) fit indicated the validity and reliability of the model. The relationship between process variables and mint leaf juice diffusion is represented by fitting the quadratic model (Eq. 15) using only critical process variables with actual values:

$$\text{Moisture diffusivity} = 2.897+0.139A+0.0069B-0.00109A^2 \quad \text{(Eq. 15)}$$

The results were significant at the 1% significance level ($p < 0.01$). As the dry air temperature increased from 40 to 70°C, the moisture diffusion increased linearly and sharply by 15.29%. This showed that dry mint leaves with a higher drying temperature had the highest moisture release. Moisture diffusivity increased with increasing dry air, probably because the kinetic energy of water molecules increased with increasing temperature. Higher kinetic energy resulted in greater molecular movement and increased diffusion rate hence increased moisture diffusivity. Raviteja *et al.* (2019) also reported similar patterns in moisture diffusivity values of dry mint leaves.

In addition, the effect of moisture emission of mint leaves on the appearance of dry air and the relative humidity level is shown in Figure 7. When the relative humidity in the drying chamber was increased from 10 to 40% in mint leaves, the propagation rate gradually decreased linearly by 13.63%. This could slow down the drying process, resulting in longer drying time and decreasing moisture diffusivity.

Conclusion

The present work demonstrated that heat pump drying was an effective method for drying mint leaves, preserving key quality attributes such as colour, ascorbic acid, and antioxidant capacity. Process optimisation revealed that drying at temperature (40°C) and relative humidity (10%) resulted in improved product quality. Notably, the antioxidant capacity of the dried samples under these conditions was found to be very similar to that of the fresh leaves. However, as the relative humidity increased from 10 to 40%, a significant decrease in antioxidant capacity was observed. These findings indicated that drying under low temperature and low humidity conditions was a promising strategy for commercial post-harvest processing, contributing to the extended quality retention of mint powder. Conversely, higher relative humidity levels in the drying environment negatively impacted the preservation of active compounds in mint leaves. These findings suggested that heat pump drying may offer advantages over conventional methods in terms of quality retention, though further studies on storage stability and shelf life are recommended.

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