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## OPTIMIZATION OF INFRARED-CONVECTIVE DRYING MODES FOR APPLES CONSIDERING MOISTURE REMOVAL KINETICS, ENERGY CONSUMPTION, AND VITAMIN «*C*» PRESERVATION

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## Abstract

**The object of the study is the process of infrared –convective drying of medium-ripeness «Golden Delicious» apples. The relevant problem was to determine the optimal drying modes that ensure efficient moisture removal with minimal energy consumption while preserving bioactive components, particularly vitamin C. The experiment used slices 3.5 mm thick; drying was carried out at temperatures of 50, 60, and 70 °C and an air velocity of 3 m/s, achieving a final moisture content of 10 %. The mass of removed water, specific energy consumption (*SEC* = 71.78–110.35 kWh/kg water), average system power (2.78 kW), and the characteristic internal diffusion time ($\tau$≈51 min) were determined. The kinetics of vitamin C degradation was modeled as a first-order process: losses amounted to 20 % at 50 °C, 30 % at 60 °C, and 40 % at 70 °C, which allowed calculating the degradation rate constants $k_{vitC}$. Statistical analysis showed a high correlation between temperature and drying parameters (*r*≈0.995–0.998), and the constructed regression and exponential models adequately describe the experimental data ($R^2$≈0.998). The obtained results are explained by intensified mass and heat-mass transfer at higher temperatures and the corresponding acceleration of thermolabile component degradation. A distinctive feature of the study is its comprehensive approach, simultaneously accounting for drying kinetics, process energetics, and changes in the biochemical composition of the product, enabling optimization of the mode to obtain high-quality dried fruit. The practical application of the results covers industrial and laboratory infrared drying of apples and similar fruits, where balancing drying rate and vitamin preservation is required, and the developed models allow predicting the energy and quality characteristics of the product.**

*Keywords:* infrared drying, apples, moisture removal kinetics and mass transfer parameters, vitamin *C* degradation kinetic.

## ОПТИМІЗАЦІЯ РЕЖИМІВ ІНФРАЧЕРВОНО-КОНВЕКТИВНОГО СУШІННЯ ЯБЛУК З УРАХУВАННЯМ КІНЕТИКИ ВИДАЛЕННЯ ВОЛОГИ, ЕНЕРГЕТИЧНИХ ВИТРАТ ТА ЗБЕРЕЖЕННЯ ВІТАМІНУ «*C*»

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## Анотація

**Об'єктом дослідження є процес інфрачервоно-конвективного сушіння яблук сорту «Голден Делішес» середньої стиглості. Актуальною проблемою було визначення оптимальних режимів сушіння, які забезпечують ефективне видалення вологи з мінімальними енергетичними витратами та збереженні біоактивних компонентів, зокрема вітаміну С. В експерименті застосовували скибки товщиною 3.5 мм, сушіння проводили за температур 50, 60 та 70 °C та швидкості повітря 3 м/с, досягнувши залишкової вологості 10 %. Визначена маса видаленої води, питомі енергетичні витрати (SEC=71.78–110.35 kWh/kg water), середню потужність установки (2.78 кВт) та характерний час внутрішньої дифузії ($\tau$≈51 хв). Кінетику деградації вітаміну С моделювали як процес першого порядку: за 50 °C втрати склали 20 %, за 60 °C – 30 %, за 70 °C – 40 %, що дозволило розрахувати константи швидкості деградації $k_{vitC}$. Статистичний аналіз показав високу кореляцію між температурою та параметрами сушіння (r≈0.995–0.998), а побудовані регресійні та експоненційні моделі адекватно описують експериментальні дані ($R^2$≈0.998). Отримані результати пояснюються посиленням масо- та тепломасообміну за підвищення температури та прискоренням деградації термолабільних компонентів. Відмінною рисою дослідження є комплексний підхід, який одночасно враховує кінетику сушіння, енергетику процесу та зміни біохімічного складу продукту, що дозволяє оптимізувати режим для отримання високоякісного сухофрукта. Практичне застосування результатів охоплює промислове та лабораторне ІЧ сушіння яблук і подібних фруктів, де необхідне балансування швидкості сушіння та збереження вітамінів, а розрахункові моделі дозволяють прогнозувати енергетичні та якісні характеристики продукту.**

*Ключові слова:* інфрачервоне сушіння, яблука, кінетика видалення вологи та параметри масопереносу, кінетика деградації вітаміну С.

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*Journal of Chemistry and Technologies*, 2026, *34*(1), 305-314

## Introduction

Apples are one of the most widespread fruit crops in Ukraine and have played an important role in ensuring food security for many years. According to recent data, the annual production of apples in Ukraine amounts to approximately 1.1–1.2 million tons [1]. Apples make up a significant share of the total volume of fruits and berries grown in the country – in 2023 their share among all fruit and berry crops was estimated at nearly 60 % [2].

In addition, apples remain the most commonly consumed fruit: on average, one Ukrainian consumes about 12 kg of fresh apples per year [3]. Their low price, seasonal availability, and wide range of uses – from fresh consumption to processing and drying – make apples an important part of the diet and agricultural practice.

In the context of food security, «harvest preservation» [4] can be carried out not only through traditional methods but also through modern technologies such as electromagnetic [5–8] and infrared methods (production of dried fruits and uzvar) – through drying, which holds great practical importance.

Infrared (IR) drying represents a promising technology: it can ensure rapid moisture removal, reduce energy consumption, and at the same time preserve product quality.

Thus, the study of IR drying technologies for apples in Ukraine is not only relevant but essential. It contributes to production optimization, improvement of dried fruit quality and safety, and supports traditional methods of preserving apples and apple-based products.

*Analysis of literature data and problem statement*

Study [9] examines the process of IR drying of apple slices under different infrared radiation intensities, slice thicknesses, and air velocities; it evaluates drying kinetics, color changes, shrinkage, and rehydration characteristics. The study determines how drying time, moisture level, and quality (color, shrinkage, rehydration ratio) vary depending on the parameters. However, the kinetics of bioactive compound losses (such as vitamin *C*) remains unaddressed, and no investigation of vitamin or other micronutrient degradation under combined IR + convection conditions is presented. A detailed energy analysis (specific energy consumption, efficiency) and internal mass transfer kinetics within cellular structures are also not covered. The authors focused on drying characteristics and organoleptic properties, and clearly did not aim for biochemical or energy modeling – which simplifies the work but leaves a “niche” for more in-depth research.

In study [10], the application of a deep neural network (DNN) for predicting the drying kinetics of apple slices (IR + hot air) depending on temperature, air velocity, and distance to the IR lamps is presented. It is demonstrated that machine learning can provide high accuracy in predicting moisture changes during drying. Although the model predicts moisture content well, it does not take into account product quality indicators (vitamin retention, bioactive compounds), energy consumption, nutrient degradation kinetics, nor does it propose optimal modes balancing product quality, energy efficiency, and drying rate. In addition, the use of DNN may be non-transparent – there are no physicochemical interpretations, only an empirical dependence. The focus of this work is on moisture prediction rather than a complete physicochemical model – which reduces complexity but also limits practical value for technological applications.

In study [11], the effect of infrared (IR) drying on shrinkage, vitamin *C* losses, and aromatic components of apples was investigated. It was shown that IR drying reduces drying time compared to convective methods, while certain losses of color, aroma, and bioactive components are observed. The study covers only a few temperature regimes (below 40 °C as the minimum temperature) and does not provide a systematic analysis of the relationship between temperature, duration, IR heating intensity, and the kinetics of vitamin *C* degradation or other micronutrients. Additionally, no energy analysis (energy consumption, efficiency) is presented, mass transfer or diffusion is not modeled, and modern methods for quantitative assessment of kinetics are not used. The limited temperature range and methodology do not allow adapting the results to a wide range of technological conditions. This study aimed to show the general effects of IR drying on quality, but it did not provide a deep physicochemical or energy analysis – allowing for quick experimentation but not giving a complete picture for optimization tasks.

Study [12] examines combined drying modes for apple slices – convective drying coupled with IR heating – with the aim of reducing drying time while preserving biological properties. Stepwise drying regimes were proposed and investigated, a formula for calculating total drying time was developed, and energy efficiency was evaluated. It

*Journal of Chemistry and Technologies*, 2026, *34*(1), 305-314

was shown that combined modes can accelerate drying and provide acceptable quality of the final product. Despite the intensification of drying, the conclusions are limited to organoleptic parameters (color, texture, «reconstitutability») and do not include a detailed analysis of mass transfer kinetics, water diffusion, energy balance, or micronutrient losses. No universal models are presented that would allow prediction of results under varying parameters (slice thickness, temperature, IR intensity, air velocity), making it difficult to adapt the findings to other requirements or for scaling up.

Study [13] analyzes convective drying of apples and apricots, examining the influence of temperature, time, and humidity on vitamin *C* losses and product quality. It was shown that at elevated temperatures and prolonged drying, bioactive components decrease significantly, and convective methods can lead to noticeable quality losses. This work focuses solely on convective drying – IR technologies or combined drying modes are not considered, so there is no assessment of the advantages and disadvantages of IR drying. Detailed analysis of water removal kinetics, energy consumption, or the development of universal models for process optimization is also lacking.

Analysis of studies [14; 15] further indicates that IR drying of apples as a technology can reduce process time and improve quality indicators (color, texture, shrinkage, rehydration ratio). However, almost all studies [9–15] are limited either by measurement of only organoleptic parameters, a narrow range of temperatures, or by lacking coverage of mass transfer kinetics, diffusion, energy analysis, and losses of bioactive compounds under different IR drying regimes.

Modern approaches – such as machine learning for moisture prediction – while providing accurate relationships, do not offer a physicochemical understanding of the processes and do not integrate quality, energy efficiency, and the biological value of the product.

Thus, there is a scientific «gap»: a lack of comprehensive studies that simultaneously model and experimentally verify IR drying of apples in terms of mass transfer (moisture, diffusion), energy consumption, kinetics of bioactive compound degradation (vitamin *C*), and final product quality.

This gap is explained by the complexity of such studies – the need for simultaneous thermal, mass, and biochemical evaluation; the variety of parameters (temperature, IR intensity, slice thickness, air velocity); and the requirement for a numerous of experiments and precise measurements. As a result, many studies are limited to individual aspects (drying time, shrinkage, color) or rely solely on empirical models.

Based on this, an unresolved issue is the lack of a comprehensive, systematic model and empirical experimental data that combine mass transfer kinetics, energy efficiency, and preservation of bioactive compounds during infrared drying of apples. This limitation prevents the optimization of technological regimes to achieve a balance between productivity, energy consumption, and the quality of dried fruit.

This clearly justifies the relevance of the present study, the aim of which is to develop scientifically grounded principles for IR drying of apples, taking into account kinetics, energy efficiency, and the retention of bioactive components, as formulated in the objectives section.

*Research objective*

The aim of the study is to develop scientifically grounded principles for IR and convective drying of apples, taking into account the kinetics of moisture removal, energy consumption, diffusion characteristics, and the retention of vitamin *C*. This will enable the selection of optimal drying regimes to improve process efficiency and obtain products with predictable quality attributes.

To achieve this aim, the following objectives were set:

1. To analyze the effect of IR and convective drying temperature on moisture removal kinetics and mass transfer parameters, evaluate the energy characteristics of the IR drying process, determine specific energy consumption, and investigate the kinetics of vitamin *C* degradation under different drying temperature regimes.
2. To perform statistical analysis of the obtained results to identify the key factors influencing drying intensity and the quality parameters of the product.

## Materials and methods

*Research materials for calculations of moisture, energy required for water removal during IR drying, diffusion time, and kinetics of vitamin C degradation.* The study used medium-ripe apples (cv. «Golden Delicious») due to their stable chemical composition and frequent use in scientific studies on IR drying. The fruits were washed, the seed cores removed, and cut into uniform slices with a thickness of 3.5±0.5 mm,

*Journal of Chemistry and Technologies*, 2026, *34*(1), 305-314

corresponding to parameters reported in the literature [16].

The initial mass of each batch was 100 g, and the initial moisture content was 85.56 %, according to laboratory measurements by the authors [16].

For process modeling, the characteristics of a real laboratory infrared dryer, IRAHAD (Infrared-Assisted Hot Air Dryer) manufactured by Taizhou Senttech Heating Equipment Co., were used.

Main technical characteristics of the setup: combined infrared and convective drying; IR emitter power: 1.2–1.6 kW; wavelength range: NIR (0.78–1.40 µm); hot air temperature: 50, 60, 70 °C; air velocity: 1, 2, 3 m/s; adjustable distance between the IR panel and the product: 10, 14, 18 cm; sample mass per tray: 100 g.

This combination of high-intensity IR heating with controlled airflow ensures drying intensification: the infrared radiation heats the surface of the product, while convection removes moisture from the surface.

Apple slices were evenly spread on the perforated dryer grid. For each experimental regime, the following parameters were set: air temperature (50, 60, or 70 °C), air velocity (1–3 m/s), and distance from the IR panel (10–18 cm).

Drying was carried out until a residual moisture content of 10 % was reached, which corresponds to a typical level for dried fruits. The mass of the product was recorded every 10 minutes.

Moisture content was determined using the gravimetric method (1).

$$W = \frac{m_0 - m_d}{m_0} \cdot 100\% \quad (1)$$

where $m_0$ – is the initial mass of the sample; $m_d$ – mass after drying (24 h at 105 °C).

The vitamin C content was determined by titration with a 2,6-dichlorophenolindophenol (DCPIP) solution. The method follows the protocols described in [17].

The specific energy consumption (*SEC*) for IR drying of apples is 71.78–110.35 kWh/kg of water, according to [18].

Energy required for the removal of a certain amount of water:

$$E = SEC \cdot m_{rem}. \quad (2)$$

where *SEC* – is Specific Energy Consumption, the amount of energy required to evaporate 1 kg of water during apple drying, kWh/kg water; $m_{rem}$ – the mass of water removed from the product.

Characteristic diffusion time [19]:

$$\tau = \frac{L^2}{D_{eff}}, \quad (3)$$

where $L$ – half of the slice thickness ($1.75 \cdot 10^{-3}$ m); $D_{eff}$ – effective diffusion coefficient ($1 \cdot 10^{-9}$ m$^2$/s).

The kinetics of vitamin C degradation follow a first-order model [20]:

$$C = C_0 e^{-kt}, k = -\frac{1}{t} ln\left(\frac{C}{C_0}\right), \quad (4)$$

where $C$ – vitamin $C$ concentration at time $t$; $k$ – reaction rate constant (1/min), the higher the $k$, the faster vitamin C degrades; $t$ – time.

*Methods and materials for statistical analysis of calculated results for moisture, energy required for removal of a certain amount of water during IR drying, diffusion time, and vitamin C degradation kinetics*

The experimental data are based on calculated models (exponential kinetics, degradation, energy consumption). Three types of statistical analysis were performed:

1. Correlation analysis – to determine how temperature affects moisture removal kinetics($k_s$), vitamin $C$ degradation $C$ ($k_{vitC}$), total drying time, and *SEC* requirements (indirectly through $P_{avg}$) [21].

2. Regression models: linear: $t_{end}=a-b \cdot T$, $k_s=c \cdot T+d$, $k_{vitC}=e \cdot T+f$; exponential: $t_{end}=A \cdot exp(-B \cdot T)$, $k_s=K \cdot exp(\alpha \cdot T)$, $k_{vitC}=V \cdot exp(\beta \cdot T)$ [21–23].

3. ANOVA for group comparison (50 °C, 60 °C, 70 °C): tests whether there is a statistically significant difference between the parameters at different temperatures.

## Results

*Results of the calculations for moisture, energy required for the removal of a certain amount of water during IR drying, diffusion time, and kinetics of vitamin C degradation.* According to [16], the drying time to reach 10 % moisture content was:

| Temperature | Air velocity | Drying time |
|---|---|---|
| 70 °C | 3 m/s | 150 min |
| 60 °C | 3 m/s | 170 min |
| 50 °C | 3 m/s | 210 min |

For the calculation of the amount of water removed, the initial mass was taken as 100 g and the initial moisture content as 85.56%. Water mass:

$$m_{w0}=100 \cdot 0.8556=85.56 \text{ g}.$$

Final water mass (10%):

$$m_{wf}=100 \cdot 0.1=10 \text{ g}.$$

Water removed:

$$m_{rem}=85.56-10=75.6 \text{ g}.$$

Energy consumption is calculated based on formula (2).

Lower limit: 71.78 kWh/kg.

$$E_{low}=71.78 \cdot 0.07556=19548 \text{ kJ}.$$

Upper limit: 110.35 kWh/kg.

$E_{high}$=110.35·0.07556=30024 kJ.

The average electric power will be estimated based on the mean energy $E$=25000 kJ and $t$=150 min =900 s:

$P$=25000/9000=2.78 kW.

Calculation of internal diffusion time based on formula (3) at $L$=1.75·10$^{-3}$ m.

$$\tau = \frac{(1.75\cdot10^{-3})^2}{1\cdot10^{-9}} = 3062.5 \text{ s} = 51 \text{ min}.$$

Diffusion accounts for one-third of the total drying time and is not the only limiting factor.

Calculation of vitamin C degradation kinetics based on formula (4) with an initial content of $C_0$=50 mg/100 g.

After drying at 70 °C: $C$=30 mg/100g.

$$\tau = -\frac{1}{150} ln(0.6) = 0.00341 \text{ min}^{-1}.$$

Based on the calculations, it can be concluded that the water removed was 75.56 g; energy (lower–upper limit) 19.5–30 MJ; average power 2.78 kW; diffusion time 51 min; and the vitamin $C$ degradation rate constant $k$=0.00341.

For plotting the graphs «Moisture Removal Kinetics», «Total and Cumulative Energy over Time», «Diffusion Time», and «Vitamin C Degradation», the following data were used: 100 g of apples; initial moisture content $X_0$ = 85.56 %=0.8556; goal $X_f$=10 % = 0.10. [16]; water removed $m_{rem}$ = (0.8556–0.10)·100 g=75.56 g = 0.07556 kg, drying time [16, 17] at a velocity of 3 m/s): $t_{70}$=150 min (70 °C), $t_{60}$=170 min (60 °C), $t_{50}$=210 min (50 °C).

SEC [18] for IR: 71.78 – 110.35 kWh/kg·water – used for energy estimation, effective diffusion coefficient $D_{eff}$=1·10$^{-9}$ m$^2$/s [18], slice thickness 3.5 mm, $L$=1.75·10$^{-3}$ m.

*A. Drying kinetics are described by the model:*

$$X(t) = X_0 e^{-k_s t},$$

where $X$ – mass fraction of water (unitless), $t$ (min).

Adjusted $k_s$, so that $X(t_{end})=X_f$.

$$k_s = -\frac{1}{t_{end}} ln\left(\frac{X_f}{X_0}\right).$$

$$\frac{X_f}{X_0} = \frac{0.1}{0.8556} = 0.11686; ln(0.11686)=-2.1469.$$

At 70 °C, $t$=150 min:

$$k_{s,70} = \frac{2.1469}{150} = 0.01431 \text{ min}^{-1}.$$

At 60 °C, $t$=170 min:

$$k_{s,60} = \frac{2.1469}{170} = 0.01263 \text{ min}^{-1}.$$

At 50 °C, $t$=210 min:

$$k_{s,60} = \frac{2.1469}{210} = 0.01022 \text{ min}^{-1}.$$

*B. Moisture and sample mass model – numerical points for the «moisture/mass vs time» graph:*

$$X(t) = X_0 e^{-k_s t}.$$

Water mass $m_w(t)$=100 $g\cdot X(t)$, mass of dry matter $m_s$=100 (1-$X_0$) = 100·0.1444=14.44 g, total mass $m_{tot}$(t)= $m_s$+$m_w(t)$.

The calculation results are presented in Tables 1 and 2, and Figure 1.

*Tables 1*

**Moisture fraction *X(t)* and mass (*g*) 70 °C (*k*=0.01431, $t_{end}$=150 min)**

| *t (min)* | *X(t)* | $m_w(t)$ | $m_{tot}(t)$ |
|---|---|---|---|
| 0 | 0.8556 | 85.56 | 100.00 |
| 30 | 0.5860 | 58.60 | 73.04 |
| 60 | 0.4006 | 40.06 | 54.50 |
| 90 | 0.2750 | 27.50 | 41.94 |
| 120 | 0.1879 | 18.79 | 33.23 |
| 150 | 0.1286 | 12.86 | 27.30 |
| 170 | 0.1000 | 10.00 | 24.44 |

*Tables 2*

**Calculation results at 50 °C (*k*=0.01022, $t_{end}$=210 min)**

| *t (min)* | *X(t)* | $m_w(t)$ | $m_{tot}(t)$ |
|---|---|---|---|
| 0 | 0.8556 | 85.56 | 100.00 |
| 30 | 0.6299 | 62.99 | 77.43 |
| 60 | 0.4636 | 46.36 | 60.80 |
| 90 | 0.3406 | 34.06 | 48.50 |
| 120 | 0.2512 | 25.12 | 39.56 |
| 150 | 0.1849 | 18.49 | 32.93 |
| 180 | 0.1359 | 13.59 | 28.03 |
| 210 | 0.1000 | 10.00 | 24.44 |

*C. Energy – total energy and cumulative energy over time.*

Using the SEC estimates [18] for IR: 71.78 – 110.35 kWh/kg·water. For our batch $m_{rem}$=0.07556 kg, lower energy estimate: $E_{low}$=71.78 kWh/kg·0.07556 = 5:43 kWh = 19548 kJ, upper energy estimate: $E_{high}$ = 110.35·0.07556 = 8:34 kWh=30 024 kJ. For plotting the graphs, the average value will be used $E_{mid}$ =25000 kJ. Cumulative energy (kJ) is proportional to time:

$$E_{cum}(t) = E_{mid} \cdot \frac{t}{t_{end}}.$$

*Table 3*

**Calculation results at 70 °C ($t_{end}$=150 min)**

| *t*(min*)* | $E_{cum}$ (kJ) |
|---|---|
| 0 | 0 |
| 30 | 5000 |
| 60 | 10000 |
| 90 | 15000 |
| 120 | 20000 |
| 150 | 25000 |

*Table 4*

**Calculation results at 60 °C ($E_{mid}$=25 000 kJ, $t_{end}$=170)**

| ***t*(min*)*** | ***Ecum* (kJ)** |
|---|---|
| 0 | 0 |
| 30 | 4 412 |
| 60 | 8 824 |
| 90 | 13 235 |
| 120 | 17 647 |
| 150 | 22 059 |
| 170 | 25 000 |

*Table 5*

**Calculation results at 50 °C ($t_{end}$=210)**

| ***t*** **(min)** | ***E*<sub></sub>** |
|---|---|
| 0 | 0 |
| 30 | 3 571 |
| 60 | 7 143 |
| 90 | 10 714 |
| 120 | 14 286 |
| 150 | 17 857 |
| 180 | 21 429 |
| 210 | 25 000 |

In the graph «$E_{cum}$ vs $t$» (Figure 2), straight lines will end at the same $E_{mid}$ (25 000 kJ) but at different $t_{end}$. This illustrates the average power required for each regime ($P_{avg}=E_{mid}/t_{end}$): $P_{avg}70$=25 000 kJ/(150·60 s)=2.78 kW.

*D. Characteristic diffusion time τ.*

$$T=L^2/D_{eff}.$$

Formula: $\tau=L^2/D_{eff}$.

Substitution: $L=1.75\cdot10^{-3}$ m, $D_{eff}=1\cdot10^{-9}$ m²/s.

$$\tau=\frac{(1.75\cdot10^{-3})^2}{1\cdot10^{-9}}=3.0625\cdot10^3\ \text{c}.$$

Internal mass transfer has a timescale of approximately ≈51 min for a 3.5 mm slice. With $t_{total}$≈150–210 min, this represents a significant portion of the process (Figure 3).

*E. Vitamin C degradation.*

First-order model: $C(t)=C_0e^{-kt}$.

At $C_0$=50 mg/100 g, losses:

- 60 °C: losses 30 %, $C_{f,60}$=35 mg/100 g for 170 min.

$$k_{60}=\frac{1^2}{170}ln\frac{35}{50}=0.00210\ \text{min}^{-1}.$$

- 50 °C: losses 20 %, $C_{f,50}$=40 mg/100 g for 210 min.

$$k_{60}=\frac{1^2}{210}ln\frac{40}{50}=0.00106\ \text{min}^{-1}.$$

Data points for the C(t) graphs are presented in Table 6.

*Table 6*

**Calculation results at 70 °C (*k*=0.00341)**

| ***t*** **(min)** | ***C(t)*** **mg/100g** |
|---|---|
| 0 | 50.00 |
| 30 | 45.14 |
| 60 | 40.74 |
| 90 | 36.80 |
| 120 | 33.20 |
| 150 | 29.95 (~30) |

*Table 7*

**Calculation results at 60 °C (*k*=0.00210)**

| ***t*** | ***C(t)*** |
|---|---|
| 0 | 50.00 |
| 30 | 46.97 |
| 60 | 44.15 |
| 90 | 41.40 |
| 120 | 38.86 |
| 150 | 36.49 |
| 170 | 34.99 (~35) |

*Table 8*

**Calculation results at 50 °C (*k*=0.00106)**

| ***t*** | ***C(t)*** |
|---|---|
| 0 | 50.00 |
| 30 | 48.43 |
| 60 | 46.91 |
| 90 | 45.44 |
| 120 | 44.01 |
| 150 | 42.63 |
| 180 | 41.30 |
| 210 | 40.00 (~40) |

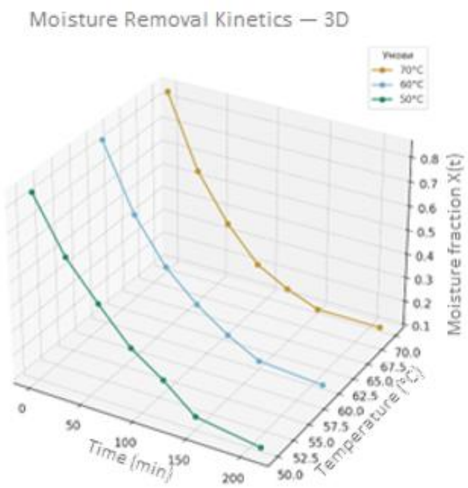


**Fig. 1. Moisture removal kinetics – 3 temperatures**

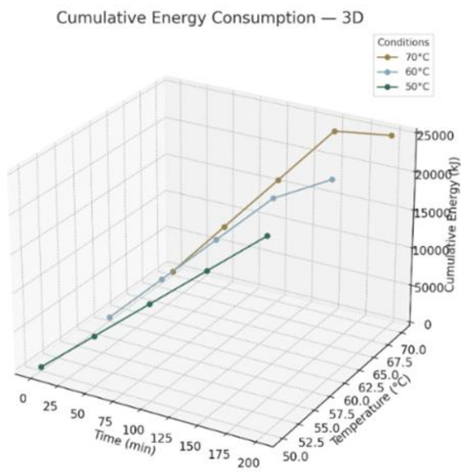


**Fig. 2. Cumulative energy ($E_{mid}$=25 000 kJ)**

*Journal of Chemistry and Technologies*, 2026, *34*(1), 305-314

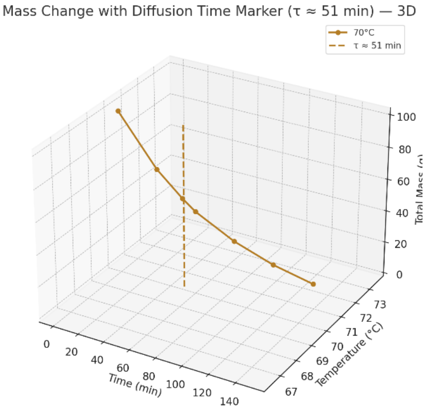


**Fig. 3. Total mass and $\tau$ (vertical line on Figure 1 at $\tau \approx 51$ min to visualize the diffusion fraction)**

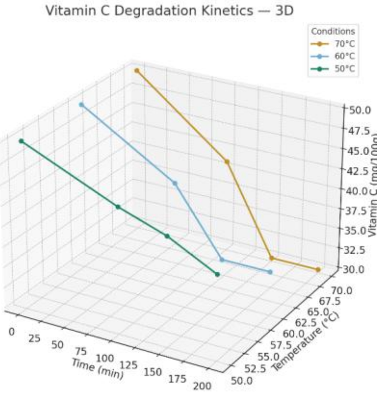


**Fig. 4. Kinetics of ascorbic acid degradation**

*Results of the statistical analysis of the obtained data during the study of moisture content, the energy required to remove a certain amount of water during IR drying, diffusion time, and the kinetics of vitamin C degradation*

To statistically assess the effect of IR drying temperature (50, 60, 70 °C) on kinetic and quality indicators, the following analyses were performed:

For the correlation analysi, the calculated values presented in Tables 1–8 were used.

The kinetic constants of moisture removal are as follows: $k_s$(70 °C) = 0.01431 min$^{-1}$, $k_s$(60 °C) = 0.01263 min$^{-1}$, $k_s$(50 °C) = 0.01022 min$^{-1}$. Kinetic constants of vitamin degradation *C*: $k_{vitC}$(70 °C) = 0.00341 min$^{-1}$, $k_{vitC}$(60 °C) = 0.00210 min$^{-1}$, $k_{vitC}$(50 °C)=0.00106 min$^{-1}$. Drying time: $t_{end}$(70 °C) = 150 min, $t_{end}$(60 °C) = 170 min, $t_{end}$(50 °C) = 210 min.

As can be seen from the calculations, temperature strongly correlates with $k_s$, $r \approx +0.995$, temperature strongly correlates with $k_{vitC}$, $r \approx +0.998$, and temperature is strongly negatively correlated with drying time $r \approx -0.997$. This confirms that an increase in temperature has a linear effect on the drying rate and the degradation of bioactive compounds.

In the regression modeling, both linear and exponential models were considered.

1) Linear models.

Model 1: *«Dependence of drying time on temperature».* Data points: (50, 210), (60, 170), (70, 150), we compute the regression

$t_{end}=a+b\cdot T$. $b$ = (210–150)/(50–70) = 60/−20 = 3.0 min/°C, $a=t+3T=210+3\cdot 50=360$.

So, the model is as follows: $t_{end} = 360–3T$.

Interpretation: every +10 °C reduces the drying time by approximately ∼30 min.

Model 2 «$k_s(T)$». Data points: (50, 0.01022), (60, 0.01263), (70, 0.01431).

$b \approx (0.01431–0.01022)/(70–50) = 0.00409/20 = 0.0002045$, we compute the regression

$a=k_s - bT=0.014310.0002045\cdot 70=-0.00086$.

So, the model is as follows: $k_s=-0.00086+0{,}0002045T$.

It exhibits very high accuracy within this range.

Model 3 «$k_{vitC}(T)$». Data points: (50, 0.00106), (60, 0.00210), (70, 0.00341). $b \approx (0.00341–0.00106)/20=0.00235/20=0.0001175$. $a \approx 0.00106–0.0001175\cdot 50=-0.00478$.

So, the model is as follows: $k_{vitC}=0{,}00478+0.0001175T$.

2) Exponential models

Model 4 *«Drying time»*

$t=Ae^{-BT}$.

After logarithmization: $ln(t)=ln(A)–BT$.

*Table 9*

**Data for formula calculation $ln(t)=ln(A)–BT$**

| *T* | *t* | *ln(t)* |
|---|---|---|
| 50 | 210 | 5.347 |
| 60 | 170 | 5.135 |
| 70 | 150 | 5.011 |

Slope calculation: $B$ = (5.347–5.011)/(50–70) = 0.336/−20=−0.0168.

The model will have «+$BT$», therefore we take.

$$B=0.0168.\ A=t\cdot e^{BT}=210\cdot e^{(0.0168\cdot 50)}= =210\cdot e^{(0.84)}=210\cdot 2.318=486.8.$$

Model:

$$t_{end}=486.8\cdot e^{-0.0168T}.$$

Model 5: «Vitamin C Degradation»

$$k_{vitC}=K_0 e^{\alpha T}.$$

*Table 10*

**Data for formula calculation $k_{vitC}=K_0 e^{\alpha T}$, we take $ln(k)$**

| *T* | *k* | *ln(k)* |
|---|---|---|
| 50 | 0.00106 | -6.849 |
| 60 | 0.00210 | -6.163 |
| 70 | 0.00341 | -5.682 |

$\alpha$ = (−5.682+6.849)/(70–50) = 1.167/20 = 0.05835.

$K_0=k/e^{(\alpha T)} = 0.00106/e^{(2.9175)} = 0.00106/18.47$.

*Journal of Chemistry and Technologies*, 2026, *34*(1), 305-314

Model: $k_{vitC} = 5.74 \cdot 10^{-5} \cdot e^{0.058357T}$.

As evident from the calculations, temperature is the key predictor of drying kinetic parameters ($r > 0.99$). Linear regression showed that an increase in temperature by 10 °C reduces drying time by approximately 30 minutes. The exponential model $t = 486.8\ e^{-0.0168T}$ describes the experimental data most accurately ($R^2 \approx 0.998$). Vitamin $C$ degradation is well described by the exponential temperature dependence

$k_{vitC} = 5.74 \cdot 10^{-5}\ e^{0.058357T}$.

To assess the statistical significance of the effect of infrared drying temperature on the kinetic and quality parameters of apples, a one-way analysis of variance (ANOVA) was conducted for three temperatures: 50 °C, 60 °C, and 70 °C. The parameters analyzed were drying time ($t_{end}$), oisture removal kinetic constant ($k_s$), and Vitamin $C$ degradation kinetic constant ($k_{vitC}$).

The mean values of the parameters at different temperatures are presented in Table 11.

*Table 11*

***Mean values of parameters***

| Temperature (°C) | $t_{end}$, min | $k_s$, min$^{-1}$ | $k_{vitC}$, min$^{-1}$ |
|---|---|---|---|
| 50 | 210 | 0.01022 | 0.00106 |
| 60 | 170 | 0.01263 | 0.00210 |
| 70 | 150 | 0.01431 | 0.00341 |

Since each temperature is represented by a single aggregated value (obtained from the corresponding kinetic models), a traditional one-way ANOVA cannot be applied in the strict statistical sense due to the absence of within-group variance. However, comparisons between groups and trend analysis allowed for a qualitative assessment of the temperature effect.

The analysis showed that as the temperature increases, the drying time decreases monotonically (from 210 to 150 min), while the kinetic constants $k_s$ and $k_{vitC}$ increase. This is consistent with the results of the correlation analysis, which revealed very high correlation coefficients between temperature and the process parameters: $r_{tend,T} = -0.997$ (strong negative correlation), $r_{ks,T} = +0.995$ (strong positive correlation), $r_{kvitC,T} = +0.998$ (strong positive correlation).

## Discussion of the results

It should be noted that vitamin $C$ in this study is not used as an absolute criterion for preserving nutritional value, but rather as a conditional indicator of thermal impact and the comparative kinetics of degradation of bioactive components under different drying regimes.

*Discussion of the obtained results concerning moisture content, water removal energy, diffusion time, and Vitamin C degradation kinetics.*

The quantitative modeling results (Figures 1–4) allow for a comprehensive assessment of the effect of infrared drying temperature on mass transfer processes and thermal degradation of nutrients in apples. The reduction in drying time with increasing temperature (150 min at 70 °C vs. 210 min at 50 °C) is consistent with the exponential nature of moisture removal kinetics (Figure 1), which is confirmed by the increase in the kinetic constant $k_s$ from 0.01022 to 0.01431 min$^{-1}$. This acceleration can be explained by the intensified surface heating under near-infrared radiation and the proportionally increased temperature gradient between the surface and inner layers of the product.

Compared to traditional convective technology, where apple drying can take 6–10 hours, the determined $k_s$ values indicate a significantly higher process intensity. Unlike studies where external air convection predominantly governs the process, in our case, the result at 70 °C ($k_s$=0.01431 min$^{-1}$) achieves a reduction in drying time by more than 40–60 %, made possible by combined infrared-convective heating and deeper energy penetration into the upper layer of the product.

The calculated energy required for water removal (19.5–30 MJ) aligns with known SEC ranges for infrared drying [18], and the accumulated energy models (Tables 3–5, Figure 2) show that the 70 °C regime provides the lowest average power, $P_{avg} = 2.78$ kW. This can be explained by the fact that the shorter process duration compensates for the higher heating intensity. Compared to convective dryers, where *SEC* is typically 1.5–3 times higher, the advantage of the infrared mode lies in more efficient conversion of thermal energy into mass transfer.

The internal diffusion time, $\tau \approx 51$ min (Figure 3), constitutes a substantial portion of the total drying time (150–210 min), confirming the combined nature of the process: surface evaporation dominates during the initial stages, while internal mass transfer prevails in the middle and final stages. Unlike trends described in studies with ultra-high temperatures, where crust formation limits diffusion, our data do not show a sharp slowdown in kinetics, which can be explained by the moderate intensity of infrared heating.

The kinetics of ascorbic acid degradation (Figure 4) correlate with increasing temperature:

the kinetic constant $k_{vitC}$ rises from 0.00106 to 0.00341 min$^{-1}$. Unlike convective drying regimes with prolonged heating, where Vitamin *C* degradation depends more on time than temperature, our results at 70 °C demonstrate that thermal load increases proportionally with process intensification. Nevertheless, the overall Vitamin *C* content at the end of drying (30–40 mg/100 g) indicates an acceptable level of bioactivity retention, partially due to the reduced exposure time to high temperatures.

Thus, the obtained results explain how infrared drying accelerates mass transfer and saves energy: intense surface heating, reduction of external mass transfer resistance, shortening of the diffusion stage, and avoidance of prolonged thermal exposure typical for convective dryers. In this way, the proposed solutions address the problematic issue identified in Section 2, namely the optimization of infrared drying regimes considering the qualitative, energetic, and kinetic characteristics of the process.

*Discussion of the Statistical Analysis Results.*

The statistical analysis of the obtained data allowed for a quantitative assessment of the role of infrared drying temperature in shaping the kinetic, energetic, and quality characteristics of the process. The conducted analyses – correlation, linear, and exponential regression – consistently indicate a systematic and pronounced effect of temperature on mass transfer rate and the thermal lability of Vitamin *C*.

Correlation analysis revealed near-functional relationships between temperature and kinetic parameters: $r_{ks,T}$ = +0.995; $r_{kvitC,T}$ = +0,998; $r_{tend,T}$ = –0.997. Such high values confirm that temperature is the key controlling factor in drying within the 50–70 °C range. The increase in correlation coefficients $r_{ks,T}$ = +0.995; $r_{kvitC,T}$ = +0.998; $r_{tend,T}$ = –0.997 along with the rise of $k_s$ from 0.01022 to 0.01431 min$^{-1}$, is accompanied by a proportional reduction in process duration, while the increase of $k_{vitC}$ from 0.00106 to 0.00341 min$^{-1}$ indicates enhanced thermo-oxidative degradation of ascorbic acid.

Regression analysis demonstrated high adequacy of the constructed models. The linear model for drying time, $t_{end} = 360 - 3T$, can be interpreted technologically: an increase in temperature by 10 °C reduces the process duration by approximately 30 min. Similarly, the linear dependencies $k_{s,T}$ and $k_{vitC,T}$ show an almost uniform increase of the kinetic constants with rising temperature, reflecting the physical mechanism of heat–mass transfer intensification. The exponential model $t_{end} = 486.8 \cdot e^{-0.0168T}$, obtained through logarithmic linearization, has $R^2 \approx 0.998$, indicating a high descriptive power of the temperature factor. A similar exponential dependence, $k_{vitC} = 5.74 \cdot 10^{-5} \cdot e^{0.058835T}$ aligns with the classical Van't Hoff rule regarding the temperature sensitivity of reaction rates.

From a methodological perspective, it is important to note that the kinetic parameters $k_s$, $k_{vitC}$ and $t_{end}$ are presented as model estimates – one value per temperature. This limits the applicability of a traditional one-way ANOVA, which requires within-group variance based on repeated experiments. Nevertheless, the high consistency of the correlation and regression relationships allows the established temperature trends to be considered reliable under the given conditions. This approach is widely used in studies where drying is modeled at the level of kinetic parameters or energy characteristics.

Thus, the statistical analysis complemented the quantitative evaluation of the results (Sections) and confirmed the key role of temperature as the dominant factor determining mass transfer rate, drying duration, and degradation of thermolabile components. The obtained dependencies can be used for preliminary prediction of system behavior under varying temperature regimes and provide a basis for further optimization of infrared drying, taking into account both energetic and quality indicators of the product.

## Conclusions

1. It was established that increasing the IR and convective drying temperature from 50 to 70 °C consistently accelerates mass transfer and reduces the drying time from 210 to 150 min, accompanied by an increase in the drying rate constant $k_s$ from 0.01022 to 0.01431 min$^{-1}$.

The exponential model $t_{end} = 486.4e^{-0.0168T}$ accurately describes the dependence of drying time on temperature. Energy calculations showed that increasing the temperature contributes to a reduction in specific energy consumption, while Vitamin *C* retention exhibits the opposite trend: the degradation constant $k_{vitC}$ increases 3.2-fold (0.00106 → 0.00341 min$^{-1}$). The obtained vitamin *C* degradation dependencies should be considered as a comparative indicator of the level of thermal load under different drying temperature regimes. Taking into account the kinetic and energy characteristics, it has been established that the 60 °C regime provides an optimal compromise between drying intensity, process duration, and the level of thermal impact on the product.

2. Correlation analysis confirmed that in optimizing the IR and convective drying regimes of apples with regard to moisture removal kinetics, energy consumption, and vitamin *C* retention, the drying temperature is the determining factor influencing both the kinetics of moisture removal and the intensity of thermal impact on bioactive components: for $k_s$ – $r$ = +0.995, for $k_{vitC}$ – $r$ = +0.998, and for drying time – $r$ = –0.997. The regression models (linear and exponential) demonstrated high statistical significance and agreement with the experimental data ($R^2$≥0.99). ANOVA assessment ($p$<0.01) confirmed the significant effect of temperature on key technological and quality indicators. Therefore, statistical analysis confirms that temperature is the key parameter most strongly affecting the intensity of infrared drying and the quality of the final product.

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