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RESEARCH ARTICLE

COMPARATIVE DRYING KINETICS AND MOISTURE DIFFUSION OF ALBANIAN AND ITALIAN ORANGE PEELS: A MATLAB–BASED ANALYSIS

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Abstract

The study carries out a mathematical comparison of the drying behaviour of orange peels from Albania and Italy under various thermal conditions and for different sample sizes. Peel samples having characteristic dimensions of 5, 10, and 15 mm were dried at 50, 100, and 150 °C in a thermostat and at 95 °C in a convective dryer. The experimental mass data were processed in MATLAB in order to determine the moisture content, the moisture ratio (MR), the drying rate (DR), and the apparent effective moisture diffusivity (Deff). The moisture transport was interpreted by means of the linearised solution of Fick's second law for slab geometry. In both cases, drying took place mainly during the falling-rate period, which indicates that internal moisture diffusion was the main controlling factor. Higher temperatures had a marked effect in speeding up the removal of moisture, and the 5 mm samples generally attained equilibrium sooner than the 10- and 15-mm samples. Differences associated with the origin of the peels were also found. At 50 °C the Italian peel dried more quickly and showed behaviour more consistent with the linearisedFickian diffusion model. At 100 °C the Italian samples showed more variable behaviourdepending on their sample length, while the Albanian ones displayed a more consistent response with respect to dimension.When dried convectively at 95 °C, the Italian peel lost moisture more rapidly, especially in the case of the 5- and 10-mm samples. The findings show that the drying behaviouris determined by the combined influence of temperature, characteristic dimension, drying method, and the origin of the material. The MATLAB–Fick approach offers a practical way of comparing moisture-transport behaviour, while the deviations observed at high temperature point to the necessity of taking into account shrinkage and structural changes in future modelling.

Introduction:-

Drying involves both heat and mass transfer and is commonly used to decrease moisture content and enhance material stability. It occurs through the transfer of thermal energy to the wet solid and the movement of moisture

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from within the material to the surface. Hence, drying temperature, air movement, material shape, initial moisture distribution, and internal structure can all strongly affect the rate at which moisture is removed [1–3].When it comes to food and plant materials, drying usually takes place mainly in the falling-rate period, it being at this stage that the internal resistance to the movement of moisture becomes more and more significant. In such cases, diffusion-based methods offer a useful engineering basis for understanding the transfer of moisture. Frequently, Fick's second law is used to calculate an apparent effective moisture diffusivity (Deff), a quantity summarising the overall response of internal moisture transport under certain assumptions regarding geometry and boundary conditions [2,3].

Temperature is one of the key operating variables in the drying process. While higher temperatures usually increase the driving force for heat transfer and speed up the movement of moisture, they can also lead to shrinkage, surface hardening, changes in porosity, and non-uniform distributions of moisture. Such structural effects can cause a departure from ideal diffusion behaviour, especially in the later stages of drying [1,4]. As a result, Deff must be regarded as an apparent transport parameter which depends on the model rather than as an invariant material constant.Sample dimension is equally important because it sets the characteristic distance moisture must diffuse before it reaches the surface; thin samples tend to dry more quickly because of their shorter diffusion path, whereas longer samples can retain moisture longer [4–6]. However, it can interact with material heterogeneity and thermal treatments, so simple sample lengths-based trends may not hold at higher temperatures.

Orange peel is a biological material which is made up of two structurally different outer and inner tissues. Variations in fruit type, cultivar, maturity stage, growing conditions, and post-harvest history can affect tissue structure and the initial distribution of moisture. Because of this, comparing orange peels from different places of origin can reveal whether a single mathematical drying model remains valid for materials subjected to the same drying conditions. However, such a comparison should be interpreted as indicating an origin-associated response rather than as proof that origin alone causes the observed differences, unless compositional and microstructural measurements are also available.Reducing the moisture content of orange peel is important for its stabilisation and subsequent valorisation in food, extraction, pectin-recovery, feed, and biomass-processing applications.Recent studies on citrus peels and related biological materials have also shown that drying kinetics and apparent moisture diffusivity are strongly influenced by temperature, sample geometry, and material structure, supporting the use of diffusion-based models for comparative analysis [8].

Computational processing allows simultaneous analysis of the experimental drying curves and the diffusion parameters. Because MATLAB provides a reproducible environment, it is possible to calculate moisture content, moisture ratio (MR), drying rate (DR), regression slopes, and apparent diffusivity from mass measurements over time. When these calculations are combined with Linearized Fick diffusion model, it becomes possible to directly compare temperature, dimension, drying configuration, and material source.The novelty of the present study lies in the direct comparison of Albanian- and Italian-origin orange peels under the same drying framework, using MATLAB-based processing and a linearisedFickian approach to evaluate differences in drying kinetics and apparent moisture diffusivity across temperature, sample length, and drying configuration.The aim of the current study was to compare drying kinetics and apparent moisture diffusion in orange peels from Albanian and Italian origin. We examined 5, 10, and 15 mm samples using thermostat drying at 50, 100, and 150 °C and convective drying at 95 °C. Moisture content, MR, DR, and Deffwere calculatedin MATLAB, and the linearised version of Fick's second law was applied to examine internal moisture transport. We paid special attention to the combined effects of temperature, sample dimension, drying method, and material differences associated with origin.

Materials and Methods:-

Raw material and experimental design:-

We examined orange peels from Albania and Italy. According to the experimental dataset, we bought fruit of both origins from the same supermarket in Tirana, Albania. The orange peels were cut into three different sample lengths: M1 = 5 mm, M2 = 10 mm, and M3 = 15 mm. These values refer to the length of the orange-peel pieces and not to peel thickness..We carried out the oven-drying experiments using a DHG heating drying oven under controlled temperature conditions at 50, 100, and 150 °C. A second set of experiments was performed in a convective dryer at 95 °C. The reported temperatures correspond to the set temperatures of the drying equipment. The internal temperature of the orange-peel samples was not measured directly during the experiments. The exact air velocity and relative humidity in the convective dryer were not recorded. For each condition, the duplicate samples were placed in the drying equipment simultaneously, and all three sample dimensions were dried at the same time under the corresponding experimental condition.

Drying experiments:-

We measured sample mass over time as drying progressed, continuing until the mass reached a stable level. Each drying condition was performed in duplicate to verify the consistency of the decreasing mass trend during drying. The MATLAB-based kinetic and diffusion analysis reported in this study was carried out using one complete experimental dataset for each condition; therefore, the duplicate runs were not averaged or used for replicate-based statistical analysis. Measurement times differed across experiments, with measurements taken at different intervals and over different total drying times. Each temperature and material origin was therefore processed separately in MATLAB.

MATLAB data processing:-

We imported the experimental mass data into MATLAB and sorted it by sample and drying time. To calculate moisture content on a dry basis, we used the dry mass (md). The MATLAB workflow produced moisture-content curves, drying-rate curves, moisture-ratio values, and Linearised Fick diffusion models for each experimental condition.

$$X_t = \frac{m_t - m_d}{m_d} \cdot 100 \tag{1}$$

wherem_t represents the sample mass at t_i.

The experimental data were arranged in MATLAB by sample and drying time for each condition. No interpolation was applied. Values of MR less than or equal to zero were treated as NaN before logarithmic transformation, and the linear regression was performed only on valid non-NaNln(MR) data points.

Drying rate and moisture ratio:-

The drying rate (DR) was calculated from the change in moisture content between two successive measurements divided by the corresponding time interval, using a consecutive-point finite-difference approach:

$$DR = -\frac{\left(X_{t+\Delta t} - X_t\right)}{\Delta t} \tag{2}$$

where X_t and $X_{t+\Delta t}$ are the moisture contents at two successive measurements, and Δt is the corresponding time interval, on a dry basis (% d.b.).

The negative sign was used so that moisture loss was expressed as a positive drying-rate value. For each experimental condition, the actual time interval between consecutive measurements was used in the calculation. We calculated the moisture ratio using the initial and equilibrium moisture contents;

$$MR = \frac{\left(X_t - X_e\right)}{\left(X_0 - X_e\right)} \tag{3}$$

where X_0, X_t, and X_e represent the initial, instantaneous, and equilibrium moisture contents, respectively.In the present MATLAB analysis, X_e was taken as the final measured moisture content for each sample, corresponding to the last recorded point of the respective drying experiment.

Apparent effective moisture diffusivity and Fick diffusion analysis:-

Internal moisture transport was evaluated using the linearised form of Fick's second law for a slab-type geometry. The natural logarithm of MR was regressed against drying time in seconds using all valid experimental data points for which MR was greater than zero. The final point, for which $X_t = X_e$ and consequently (MR = 0), was excluded because (ln(0)) is undefined. No additional linear region was selected manually.The slope obtained by linear regression was used to calculate apparent effective moisture diffusivity according to the MATLAB implementation:

$$D_{eff} = \frac{-\left(slope \cdot L^2\right)}{\pi^2} \tag{4}$$

where L represents the characteristic length assigned to the orange-peel sample in the MATLAB calculation, corresponding to the sample lengths of 5, 10, and 15 mm used in the experimental design. These values represent the length of the peel pieces rather than their sample lengths. Because the model applies a simplified slab-type geometry and does not account for time-dependent shrinkage or changes in sample geometry, the calculated Deff values are interpreted as apparent effective moisture diffusivities.The linearisedFickian model was applied under the simplifying assumptions of constant apparent moisture diffusivity, uniform initial moisture distribution, constant sample geometry during drying, negligible external mass-transfer resistance, and equilibrium moisture conditions at the sample boundary. These assumptions provide a practical basis for comparative analysis but may not be fully satisfied in biological materials, particularly at higher drying temperatures where shrinkage, surface hardening, and structural changes may occur.The regression slope was used within the MATLAB calculation to estimate the apparent effective moisture diffusivity (Deff). Detailed regression diagnostics, including standard error and confidence intervals, were not retained in the output used for the present comparative analysis. Therefore, the Fickian model is used here primarily as a comparative framework for evaluating moisture-transport behaviour under the investigated drying conditions.

Comparative analysis:-

Although each drying condition was performed in duplicate, the present MATLAB-based comparative analysis was conducted using one complete time-series dataset for each condition. The duplicate runs were used to verify the consistency of the drying trend and were not combined for replicate-based statistical analysis. Consequently, inferential statistics and mean ± standard deviation values are not reported, and the comparisons presented in this study are descriptive.

Results and Discussion:-

General drying behavior:-

The moisture content of both the Albanian and Italian orange peels decreased gradually as drying continued. The experimental curves were mainly characterised by the falling-rate phase and did not show a clearly maintained constant-rate phase. This shows that the movement of moisture within the material was the main resistance throughout most of the drying process. The MATLAB linearizations of ln(MR) plotted against time generally showed behaviour consistent with the linearisedFickian diffusion model, although deviations appeared under certain conditions, in particular during late-stage drying and at high temperature.

Effect of temperature:-

Temperature strongly influenced the drying rate; at 50 °C, the drying process was slow and took the longest to reach equilibrium. At 95–100 °C, moisture removal became much faster, and at 150 °C the initial drop in moisture content was the fastest. At 150 °C, the observed mass loss should be interpreted with caution, since thermal degradation, browning, structural collapse, chemical changes, and surface hardening may contribute to the measured mass decrease in addition to moisture removal. These effects were not measured separately in the present study.The data also show that the apparent Deff increases as the temperature rises.At 50 °C, the apparent effective moisture diffusivity values were 8.0902×10^{-10}, 3.1391×10^{-9}, and 8.0565×10^{-9} m^2/s for M1, M2, and M3, respectively, while under convective drying at 95 °C the corresponding values were 2.3267×10^{-9}, 9.8107×10^{-9}, and 2.0932×10^{-8} m^2/s. This behaviour agrees with greater thermal activation of the moisture transport process, but the curves at high temperatures should not be interpreted solely in terms of ideal diffusion, since structural changes might modify the effective transport path.

The effect of sample dimension:-

The 5 mm sample (M1) usually dried more quickly than M2 (10 mm) or M3 (15 mm). This was especially noticeable with the Albanian peel at 50 and 100 °C and when convectively drying at 95 °C. Because M1 has a shorter characteristic transport distance, moisture needs to migrate less. M2 generally exhibited behaviour between the other two, while M3 retained moisture for a longer period. Nevertheless, at 150 °C the dimensional trend became less regular, showing that sample length alone was not enough to account for all observations under severe thermal conditions to account for all observations under severe thermal conditions.

Albanian orange peel:-

For the Albanian material, the dimensional effect was relatively regular. At 50 °C, M1 displayed the quickest reduction in moisture and attained equilibrium before the longer samples. The same pattern was seen at 100 °C, where M1 once again dried more rapidly, and M3 had the slowest overall response. At 95 °C under convective conditions, M1 showed faster moisture transfer, M2 showed intermediate behaviour, and M3 retained moisture the longest. The data thus indicate a strong interaction between temperature and transport distance in the Albanian peel.

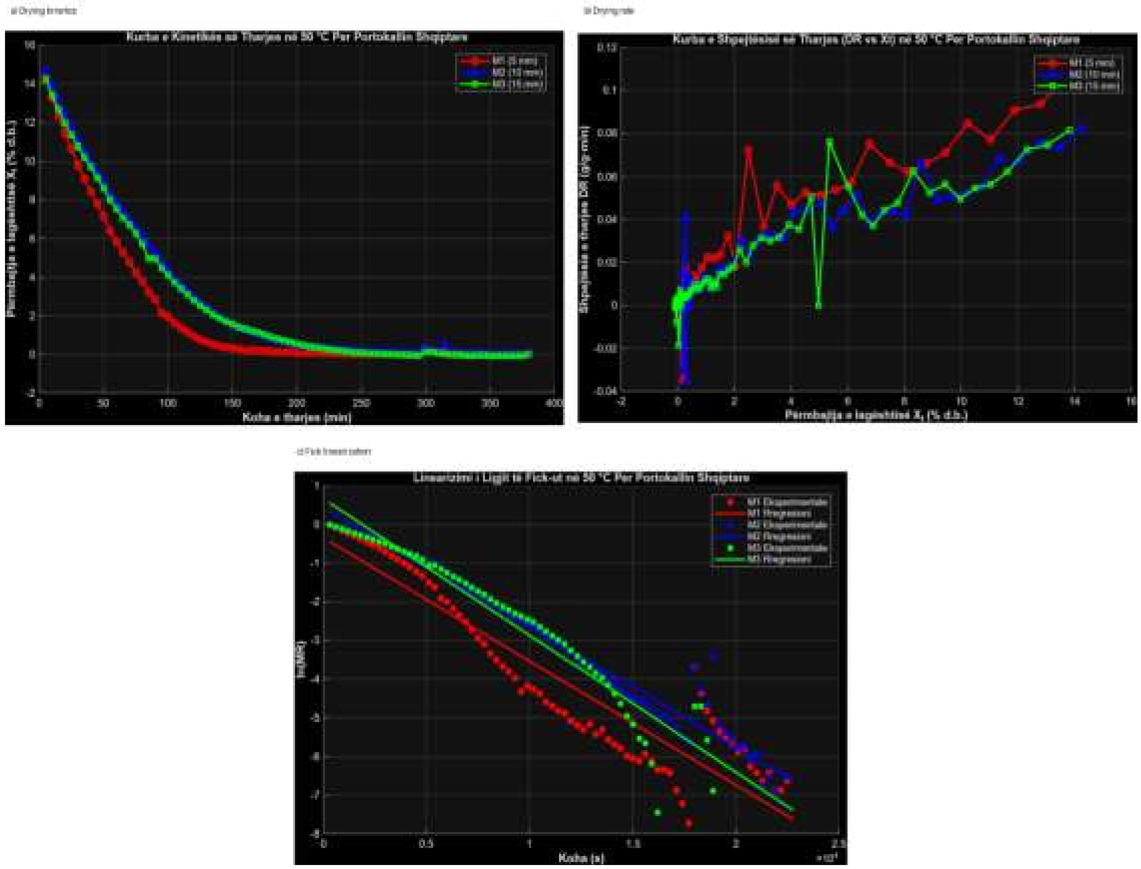

Figure 1. The MATLAB drying kinetics curve, drying rate, and Linearized Fick diffusion model for Albanian orange peel at 50 °C.

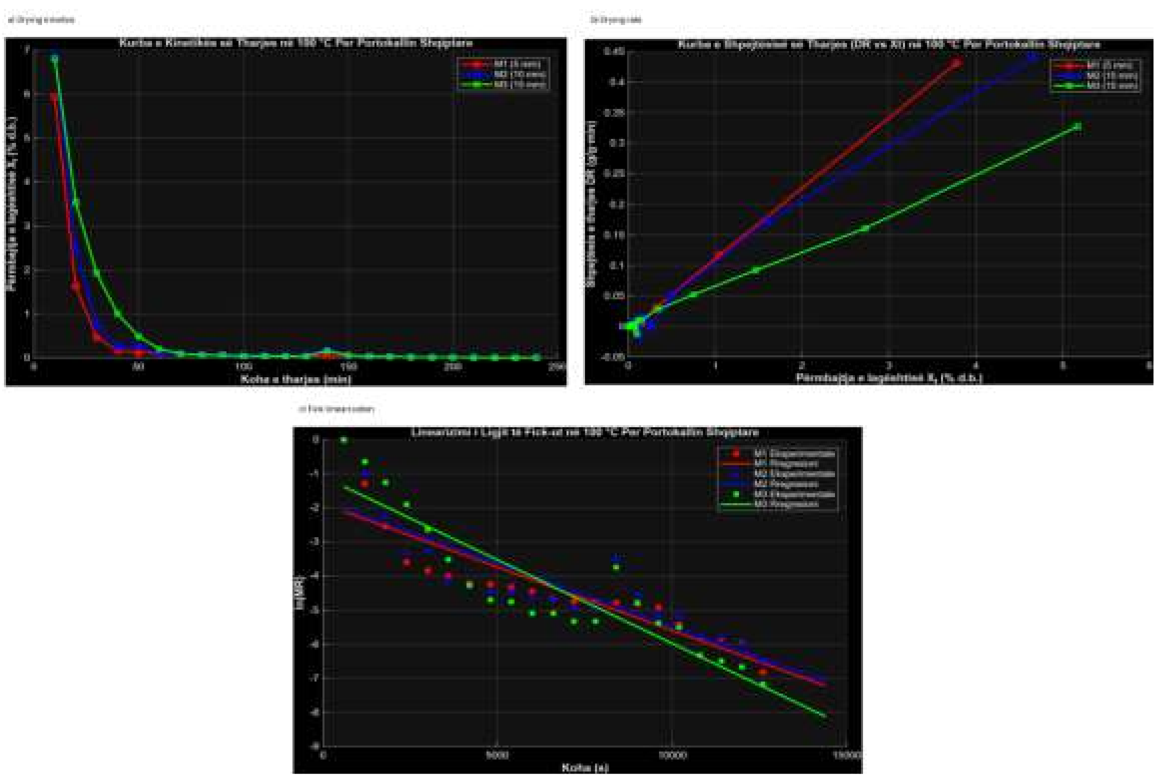

Figure 2. The MATLAB drying kinetics, drying-rate curve, and Linearized Fick diffusion model for Albanian orange peel at 100 °C.

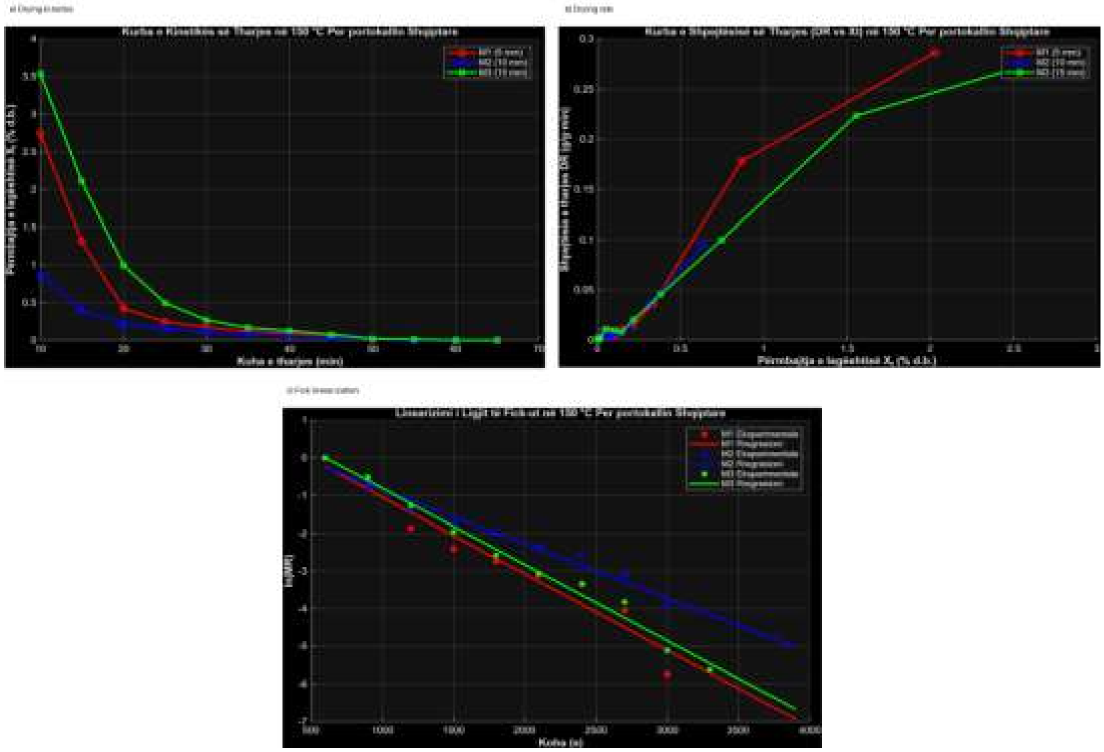

Figure 3. The MATLAB drying kinetics, drying-rate curve, and Linearized Fick diffusion model for Albanian orange peel at 150 °C.

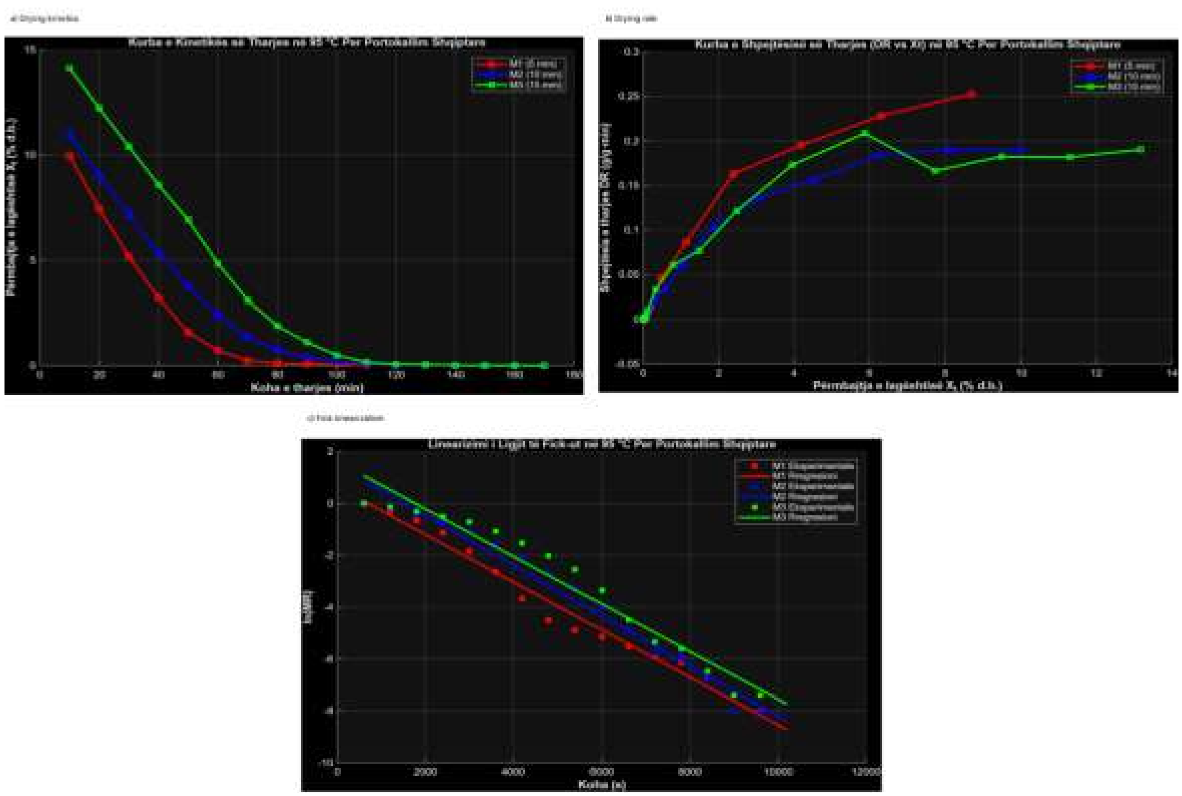

Figure 4. The MATLAB results showing the drying kinetics, drying-rate curve, and Linearized Fick diffusion model for Albanian orange peel when subjected to convective drying at 95 °C.

Italian orange peel:-

The Italian peel also showed a faster drying rate as the temperature rose, but its behaviour varied more from one dimension to another. At 50 °C, the process took several hours to reach mass stabilisation, with M1 achieving this earlier than the longer samples. At 100 °C, M1 attained a nearly constant mass much earlier, although the ln(MR) versus time plots, in the absence of direct measurements of shrinkage and porosity, showed some deviations in the later stages. At 150 °C, moisture loss was very rapid, and the order of the samples by drying rate became less consistent. This behaviour may be associated with shrinkage, surface hardening, changes in porosity, or a non-uniform initial moisture distribution; however, these mechanisms were not measured directly and therefore remain possible explanations rather than experimentally confirmed causes.

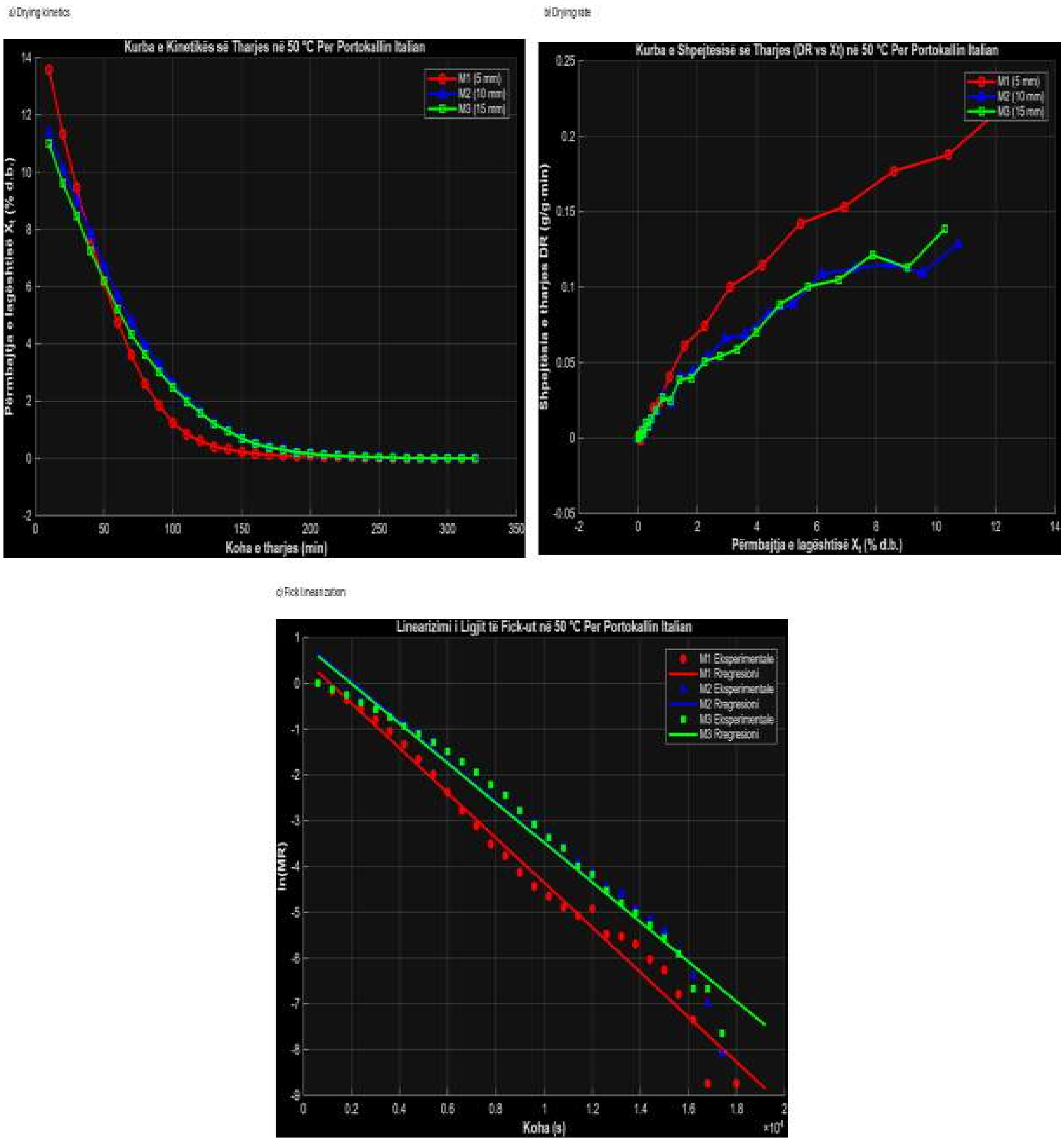

Figure 5. The drying kinetics, drying-rate curve, and Linearized Fick diffusion model for Italian orange peel at 50 °C.

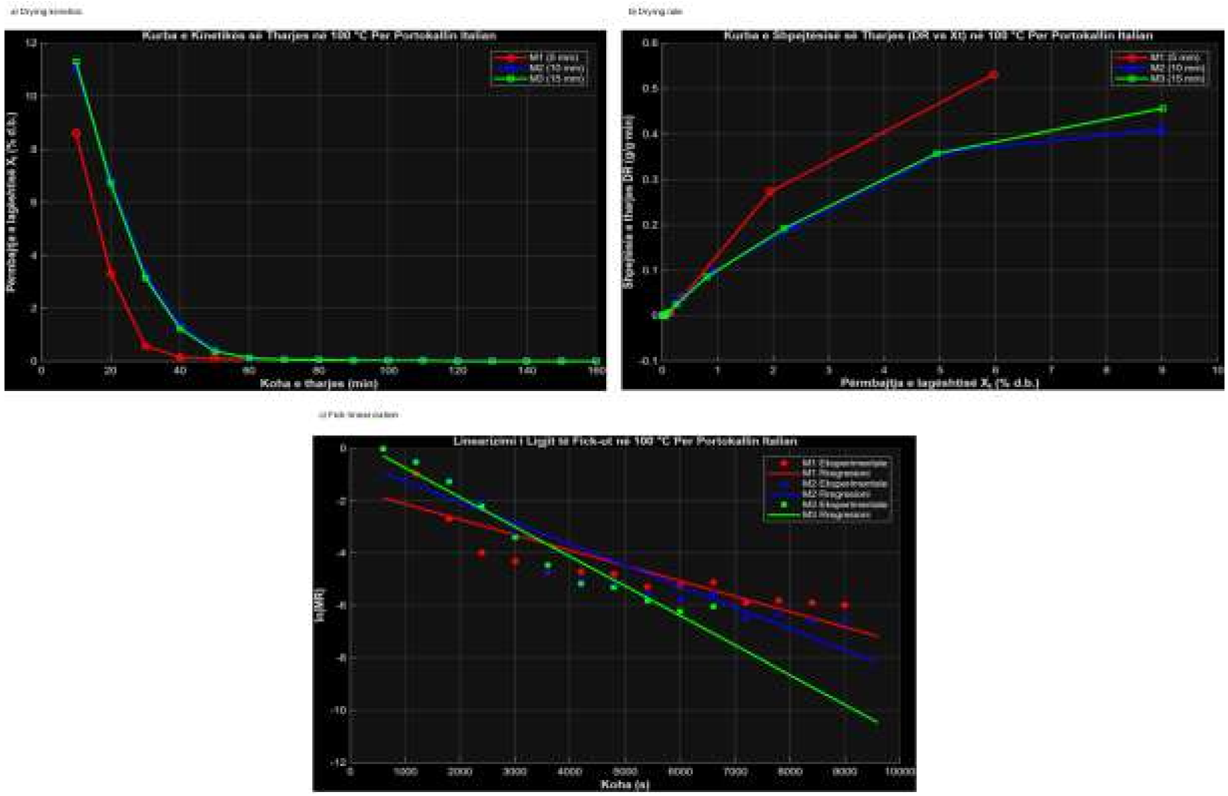

Figure 6. The drying kinetics, drying-rate curve, and Linearized Fick diffusion model for Italian orange peel at 100 °C.

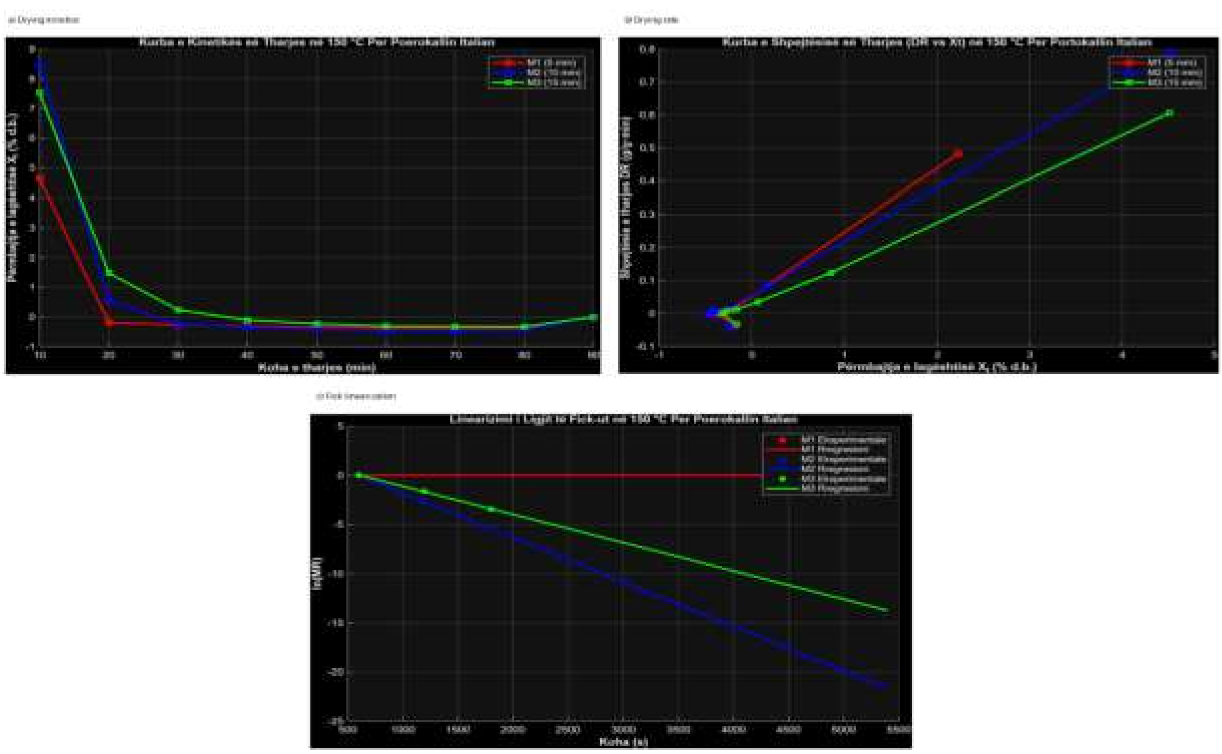

Figure 7. The drying kinetics, drying-rate curve, and Linearized Fick diffusion model for Italian orange peel at 150 °C.

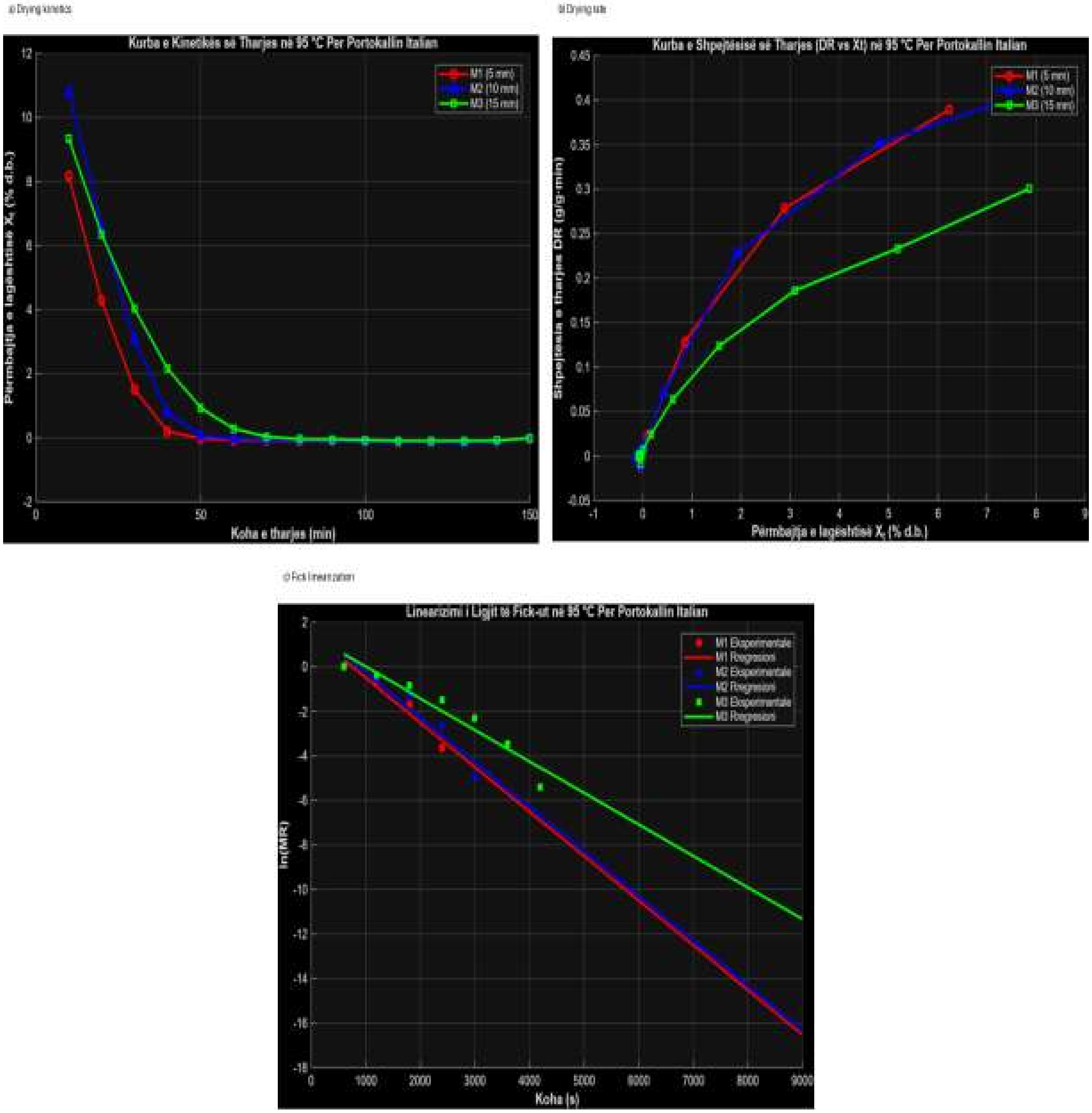

Figure 8. The MATLAB results showing the drying kinetics, drying-rate curve, and Linearized Fick diffusion model for Italian orange peel when subjected to convective drying at 95 °C.

Origin-associated differences:-

The evidence shows that both materials showed drying behaviour broadly consistent with the linearisedFickian diffusion model, but differed in the intensity and regularity of their response. At 50 °C, the Italian peel showed faster drying kinetics and behaviour more consistent with the linearisedFickian diffusion model. At 100 °C, the Albanian peel showed a more distinct sequence depending on sample length, whereas the Italian peel showed greater variation with sample dimensions. Moreover, during oven drying at 100 °C, the Italian peel stabilised after approximately 140–150 minutes, whereas the Albanian peel required approximately 240 minutes to reach mass stabilisation. These differences are interpreted as origin-associated responses rather than direct geographical effects, since cultivar, maturity, storage history, tissue structure, wax content, composition, and other physicochemical characteristics were not independently measured in the present study.

Convective drying at 95 degrees Celsius:-

Convective drying at 95 °C resulted in strong moisture removal for both materials. For the Albanian peel, the 5 mm piece dried fastest, whereas larger dimensions required more time to reach equilibrium. The Italian peel also dried rapidly, with the data indicating especially high drying rates for M1 and M2. The Linearized Fick diffusion models showed steeper negative slopes for these Italian samples, indicating higher apparent Deff. Altogether, the findings indicate that forced convection enhanced both external heat and mass transfer, even though internal diffusion was still important.The difference between convective drying at 95 °C and oven drying at 100 °C should not be attributed to the 5 °C temperature difference alone, since the two drying configurations also differ in air movement and in the associated heat- and mass-transfer conditions.

Fick diffusion modelling and MATLAB implementation:-

The MATLAB procedure offered a reliable method for converting mass measurements into values for moisture content, DR, MR, ln(MR), and apparent Deff. The approximately linear sections of the ln(MR) versus time plot justify applying Fick's second law for comparison. However, the model assumes simplified geometry and does not account for time-dependent shrinkage or structural changes. As a result, the discrepancies between the experimental data points and the regression line, especially at 150 °C and during the later stages of drying, should be regarded as significant indications of the model's limitations rather than merely experimental noise.

Process interpretation and limitations:-

Based on the drying time and qualitative behaviour described in the dataset, 100 °C proved a useful intermediate thermostat temperature: drying was much faster than at 50 °C, but the curves did not show the same clear high-temperature behaviour as at 150 °C. However, this temperature is not consideredoptimised because product quality, chemical composition, energy consumption, shrinkage, and microstructure were not measured directly. The main limitations include the use of a simplified Fickian diffusion model, the lack of direct measurements of shrinkage and porosity, the absence of direct measurements of shrinkage and porosity, and the absence of statistical analysis at the replicate level in the dataset.Compositional and physicochemical properties such as pectin, cellulose, hemicellulose, soluble solids, wax content, porosity, and tissue structure were not measured in the present study; therefore, their potential influence on the observed drying differences is considered only as a possible explanation and not as an experimentally confirmed mechanism.The 150 °C condition was included as a high-temperature experimental case to examine the drying response under more severe thermal treatment and to compare it with the lower-temperature conditions.

Conclusions:-

This study showed that the drying behaviour of Albanian and Italian orange peels was influenced by the combined effect of temperature, the size of the sample, the drying configuration, and the material characteristics associated with the origin. In all the conditions examined, moisture removal took place mainly during the falling-rate phase, which shows that internal moisture transport was the main mechanism responsible for the drying process. Raising the drying temperature from 50 °C to 150 °C greatly increased the rate of moisture removal, and the 5 mm samples generally attained a steady moisture level sooner than the 10 mm and 15 mm samples since they had a shorter path for moisture transport.

Even though both materials had the same general drying mechanism, there were clear differences in their kinetic behaviour. The orange peel from Albania displayed a more regular relationship with the size of the sample, while that from Italy generally dried more quickly but with greater variation as the dimensions were changed. The most obvious practical difference was seen when thermostat drying at 100 °C was carried out, the Italian peel reaching stabilisation after about 140 to 150 minutes whereas the Albanian peel took about 240 minutes. During convective drying at 95 °C, both materials showed rapid removal of moisture, with the Italian peel showing a particularly strong response for the 5 and 10 mm samples.

The use of MATLAB to analyse the experimental data allowed for the systematic calculation and visualisation of the moisture content, the moisture ratio, the drying rate, and the apparent effective moisture diffusivity. The fact that there is approximately a linear relationship between ln(MR) and drying time over large sections of the drying curves means that Fick's second law can be used as a practical comparative model for the orange peels under investigation. Yet the deviations seen at the later stages of drying, especially at 150 °C, indicate that the constant-geometry Fick-based diffusion approximation does not fully capture the physical changes taking place in the material; it therefore follows that the calculated Deff values must be regarded as apparent effective diffusivities and not as intrinsic material constants.

From a process perspective, 100 °C represented a useful intermediate thermostat condition in the present dataset, providing substantially shorter drying times than 50 °C without the pronounced high-temperature behaviour observed at 150 °C. However, this condition should not be considered a fully optimised drying temperature because energy consumption, chemical composition, antioxidant retention, essential-oil preservation, colour, and other product-quality parameters were not measured.

Overall, the study shows that origin-associated material differences should be considered together with temperature and sample length when comparing orange-peel drying performance. The combined experimental and MATLAB–Fick approach provides a useful framework for screening and comparing drying conditions. Future studies should include replicate-based statistical analysis, direct measurements of shrinkage and microstructure, and quality and energy assessments to determine whether the origin-associated kinetic differences observed here persist under controlled and industrially relevant conditions.

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