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HEAT AND MASS TRANSFER ANALYSIS DURING HEATING OF MILK

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ABSTRACT:
A comprehensive analysis was conducted to understand how size impacts the convective transfer properties during the greenhouse drying of khoa, a heritage dairy product. The experimental setup explored three different dimensions of khoa samples, while keeping the overall mass constant at 100g. The researchers utilized specimens with varying dimensions: small (0.025 × 0.02 × 0.015 m3), medium (0.0375 × 0.03 × 0.015 m3), and large (0.075 × 0.06 × 0.015 m3). The drying took place in a specially designed roof-style greenhouse with dimensions of 1.2 × 0.8 m2. Each sample underwent drying at normal atmospheric conditions until reaching a steady mass.
The team applied straightforward linear regression techniques to analyze the experimental findings, which helped identify the crucial constants in the Nusselt number equation. This mathematical approach facilitated the determination of convective heat transfer coefficients. The scope of research extended to calculating mass transfer coefficients as well. The findings revealed that smaller sample sizes corresponded to enhanced transfer properties, with the smallest khoa pieces showing superior convective heat and mass transfer coefficients. To ensure scientific rigor, the researchers incorporated percentage uncertainty calculations to validate their experimental methodology.
Keywords:Natural convection drying, Dairy product dehydration, Heat transfer analysis, Greenhouse processing, Mass transfer dynamics.

INTRODUCTION :

Solar power represents one of nature's most sustainable and environmentally friendly energy sources. Its potential for product dehydration has gained significant attention in recent years, offering an efficient alternative to conventional drying methods. While traditional open-air drying techniques expose products directly to sunlight, they often face challenges such as contamination from dust, insects, and environmental pollutants, potentially compromising product quality.Enter the innovative greenhouse drying system, which addresses these limitations by creating a controlled environment for product dehydration. This method employs a sophisticated approach where items are strategically arranged on specialized trays within an enclosed structure. The greenhouse's transparent plastic covering allows solar radiation to penetrate while protecting the products from external contaminants. The drying process occurs through either natural air circulation or mechanically assisted airflow, depending on specific requirements.[1]
What sets greenhouse drying apart is its remarkable efficiency in moisture removal. The enclosed design creates optimal conditions for even heat distribution, leading to consistent drying across all products. This technological advancement not only enhances the final product quality but also significantly reduces processing time compared to traditional methods. The controlled environment minimizes the risk of spoilage and ensures better preservation of nutritional content.The greenhouse drying technique represents a perfect blend of sustainable practices and modern technology. By harnessing solar energy, it eliminates the need for fossil fuels, making it both cost-effective and environmentally responsible. The system's versatility allows for year-round operation, adapting to various weather conditions while maintaining consistent drying performance. This innovation marks a significant step forward in sustainable food processing and preservation techniques.In the rich tapestry of Indian culinary heritage, khoa stands as a fundamental dairy product, crafted through a meticulous process of heat concentration and partial dehydration of milk. This traditional ingredient serves as the cornerstone for creating an array of beloved Indian sweets, deeply rooted in the country's cultural fabric. The production of khoa in India is substantial, with annual manufacturing

reaching approximately six hundred thousand tonnes, primarily within the private and unorganized sectors, consuming roughly seven percent of the nation's total milk production.The composition of khoa, particularly its moisture content, presents unique challenges in terms of preservation. This residual moisture creates an environment conducive to microbial proliferation, making the product susceptible to spoilage. Several critical factors influence the longevity and quality of khoa, with moisture level being paramount among them. Other significant determinants include the temperature at which it is stored, the quality of milk used in its preparation, the hygiene standards maintained during production, and the effectiveness of packaging methods employed.[2] Of particular concern is the growth of molds within khoa, which can rapidly compromise its quality. These microorganisms not only cause visible deterioration through unsightly discoloration but also impart unpleasant flavors that render the product unpalatable. Interestingly, research has demonstrated that exposure to solar radiation proves effective in reducing microbial populations, offering a natural method for enhancing the product's stability.The preservation of khoa quality remains a significant challenge for India's dairy industry, especially given its widespread production in small-scale facilities. Understanding and controlling these various factors becomes crucial for maintaining the product's safety and extending its shelf life, thereby ensuring this traditional dairy product continues to play its vital role in Indian sweet-making traditions while meeting modern food safety standards.

The transformation of milk into khoa involves intricate physical processes where heat and mass transfer work in tandem. As this continuous drying unfolds, the heat energy reaching the khoa's outer layer accomplishes two key objectives: the main one being moisture extraction through vaporization's latent heat, while the secondary effect raises the surface warmth through sensible heat transfer, enabling water molecules to transition into the surrounding air. Within khoa's structure, moisture moves outward because of differences in vapor pressure between the product's core and the environment. When studying how quickly khoa dries, scientists have identified the convective heat transfer coefficient as a key factor, since it determines how effectively heat flows from the air to the product during drying. This heat flow pattern plays a decisive role in both the drying system's performance and the final quality of the khoa. Previous research has extensively explored various aspects of drying agricultural products. Notable investigations include the assessment of convective mass transfer coefficients for differently shaped jaggery pieces under controlled conditions. These studies consistently demonstrated that forced convection yields higher transfer coefficients compared to natural convection methods. Further research looked into how jaggery's size and form, while keeping a constant weight, affects turbulent mass transmission ratios in both organic and induced turbulence scenarios in climate controlled environments.[2]

Recent scientific investigations have delved into the drying behavior of khoa through extensive experimentation conducted over several days. Researchers systematically evaluated two primary methods: traditional sun drying and modern greenhouse techniques, analyzing both passive and mechanically-assisted air circulation systems. The study utilized uniform khoa blocks measuring $0.09 \times 0.06 \times 0.015$ cubic meters as test specimens. Results demonstrated that mechanical air circulation yielded superior heat transfer rates compared to passive circulation. A notable observation was the gradual decrease in heat transfer efficiency from the initial to the final day of the drying process, with coefficients fluctuating between 0.54 and 1.09 W/m2 °C.

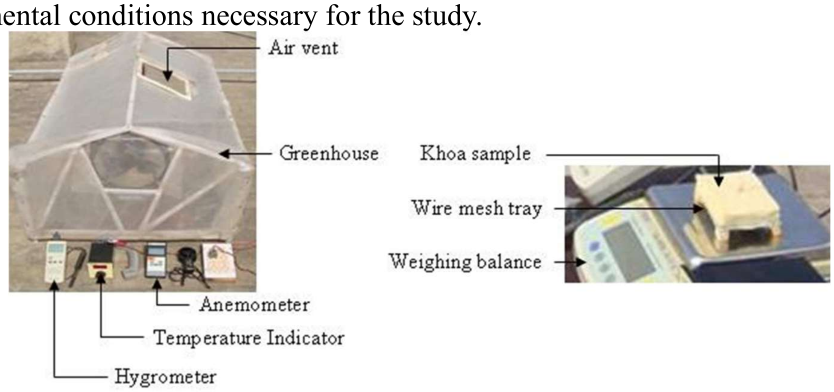
Our research extends this knowledge base by exploring the relationship between dimensional variations and their impact on both heat and mass transfer dynamics during khoa dehydration. The experimental design maintains consistent mass while employing natural air circulation within a greenhouse environment. This investigation holds practical significance, particularly for enhancing greenhouse architectural specifications to achieve optimal moisture content for extended khoa preservation. The outcomes of this research are expected to make substantial contributions to food preservation science, potentially transforming conventional drying approaches by improving operational efficiency and end-product characteristics. Understanding these critical correlations between product dimensions and transfer rates will enable the development of advanced drying methodologies that effectively balance energy consumption with preservation requirements.[3]

MATERIALS AND METHODS :

For this experimental investigation, a greenhouse structure was designed and constructed with specific dimensions and materials. The greenhouse featured a traditional roof-type even span design, encompassing an efficient floor space of 1.2 meters by 0.8 meters. The framework was constructed using durable PVC piping, while the exterior was enveloped with a 200-micron UV-resistant film covering to ensure optimal light transmission and temperature control.

The architectural design incorporated strategic height measurements, with the central peak reaching 0.6 meters and side walls extending to 0.4 meters. To facilitate natural air circulation and maintain appropriate ventilation, a carefully positioned roof vent was integrated into the design, providing an effective opening area of 0.043 square meters. This ventilation system played a crucial role in maintaining optimal conditions within the greenhouse environment.[4]

The comprehensive experimental setup, including both the greenhouse drying system and the khoa sample under investigation, has been visually documented and is presented in Figure 1 for reference. This carefully planned design ensured efficient operation while maintaining controlled environmental conditions necessary for the study.



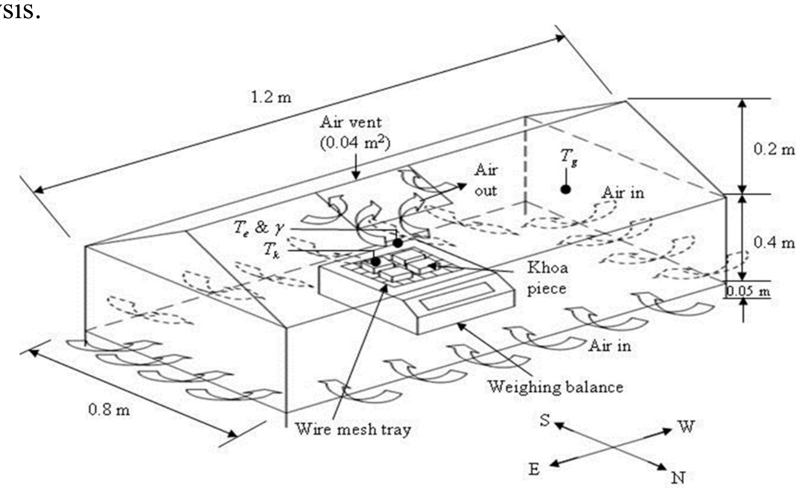
"Fig. 1: A Photographs of Experimental Unit"

To optimize solar radiation capture, the greenhouse was purposefully oriented along the east-west axis. The investigative trials were conducted using khoa samples, each weighing precisely 100 grams, formed into three distinct dimensional configurations: small pieces measuring 0.025 × 0.02 × 0.015 m3, medium pieces of 0.0375 × 0.03 × 0.015 m3, and large pieces sized at 0.075 × 0.06 × 0.015 m3.

For each experimental run, khoa specimens were carefully prepared with a uniform thickness of 1.5 centimeters, arranged in a single layer configuration. The specimens were arranged on a custom-fabricated mesh platform constructed from wire, spanning dimensions of 9 centimeters in width and 6 centimeters in length. This platform was carefully situated on an advanced electronic scale - the TJ-6000, a product of the Indian company Scaletech. This precision instrument could handle weights up to 6 kilograms while maintaining exceptional precision, capable of measurements within 0.1 grams.

Temperature measurements throughout the experiment were obtained using meticulously calibrated copper-constantan thermocouples. These sensors were integrated with a sophisticated ten-channel digital temperature indicator, providing readings accurate to 0.1 degrees Celsius. Surface temperature monitoring was achieved through the strategic placement of four thermocouples across the khoa samples, with the mean value being recorded for analysis. To ensure measurement precision, all thermocouples underwent rigorous calibration against a ZEAL thermometer, a high-quality instrument manufactured in England.[5]

The monitoring of environmental parameters was carried out using sophisticated measurement equipment. To track both relative humidity (γ or RH) and temperature directly above the khoa surface, researchers utilized a high-precision Lutron-HT 3006 digital sensor (Taiwan).
This state-of-the-art device delivered remarkable measurement precision, capable of detecting humidity changes of 0.1% and temperature variations of 0.1°C. The entire experimental configuration, detailing specific dimensions and sensor placement locations, was meticulously captured and displayed through a detailed technical drawing in Figure 2.
This carefully controlled experimental environment enabled precise monitoring of all critical parameters affecting the drying process, ensuring the collection of reliable and reproducible data for subsequent analysis.



“Fig.2:ASchematicViewofExperimentalUnit”

SAMPLE PREPARATION AND OBSERVATIONS:
The preparation of khoa followed a time-honored traditional method, refined through generations. Fresh milk was gently heated on an electric hot plate in a high-grade aluminum open pan. Throughout the process, constant stirring and careful monitoring ensured the mixture reached the perfect consistency. Once this was achieved, the heating was stopped, and the khoa was left to cool naturally to room temperature.
Using specially crafted wooden molds, the khoa was then shaped into precise cuboid pieces of varying dimensions. Three different sizes were created: the smallest measuring 0.025 × 0.02 × 0.015 cubic meters, a medium size of 0.0375 × 0.03 × 0.015 cubic meters, and the largest pieces measuring 0.075 × 0.06 × 0.015 cubic meters. Each batch maintained a consistent total mass of 100 grams, ensuring uniformity across all experimental samples.[6]
To maintain the integrity of the research, fresh khoa samples were prepared following identical procedures for each experimental iteration. The researchers established an hourly observation interval to monitor the drying process effectively.This methodical approach to sample preparation and experimental design ensured reliable and reproducible results, essential for scientific investigation into khoa's drying characteristics under controlled conditions.[7]

PROCEDURE:
In this experimental investigation, precise measurements were conducted using khoa samples, each carefully measured to maintain a consistent initial mass of 100 grams. The experimental setup featured a specialized wire mesh tray positioned directly above a digital weighing balance, allowing for accurate real-time mass measurements. To track moisture loss, researchers calculated the difference between consecutive mass readings of the khoa samples.

During the dehydration process, meticulous data was gathered every hour, encompassing several vital measurements: moisture extraction velocity from specimens, khoa's exterior thermal readings, greenhouse moisture content, air temperature directly over the khoa layer, and external environmental heat levels. The specimens underwent drying until they achieved mass equilibrium, signifying complete moisture evaporation had occurred and the process was complete.

This methodology enabled researchers to carefully monitor the dehydration process while maintaining precise control over experimental conditions. The systematic approach to data collection ensured that all relevant parameters affecting the drying process were thoroughly documented and could be analyzed to understand their relationships and impacts on the final product.[8]

THEORETICAL CONSIDERATIONS:

Thermal Modeling and Computation Technique:

In the study of natural convection heat transfer during evaporation, we can express the relationship between various dimensionless parameters through the Nusselt number correlation. The fundamental equation connecting the convective heat transfer coefficient (hc) with the Grashof and Prandtl numbers takes the form:

The Nusselt number, representing the ratio of convective to conductive heat transfer, relates to other parameters as:

$Nu = hc\ X/Kv = C(Gr\ Pr)n$

By rearranging this equation, we obtain the convective heat transfer coefficient:

$hc = (Kv/X)C(Gr\ Pr)n$

During the evaporation process, the heat transfer rate can be expressed through a relationship involving vapor pressure differences:

$Qe = 0.016hc[P(Tk) - \gamma P(Te)]$

When we incorporate the previously derived expression for hc, the equation transforms into:

$Qe = 0.016(Kv/X)C(Gr\ Pr)n[P(Tk) - \gamma P(Te)]$

To determine the actual moisture evaporation rate, we must consider several additional factors. By dividing the heat transfer rate by the latent heat of vaporization (λ) and accounting for the drying surface area (At) and time interval (t), we can calculate the mass of evaporated moisture.

For mathematical simplicity, let's define:

$Z = 0.016(Kv/X)(1/\lambda)[P(Tk) - \gamma P(Te)]AtT$

This allows us to express the relationship as:

$mev/Z = C(Gr\ Pr)n$

Taking the natural logarithm of both sides yields a linear relationship:

$\ln(mev/Z) = \ln(C) + n \ln(Gr\ Pr)$

This equation follows the standard linear form y = mx + c, where:

$y = \ln(mev/Z)$

$m = n$

$x = \ln(Gr\ Pr)$

$c = \ln(C)$

Using linear regression analysis, we can determine the constants through:

$m = (N\sum xy - \sum x\sum y)/(N\sum x^2 - (\sum x)^2)$

$c = (\sum x^2\sum y - \sum x\sum xy)/(N\sum x^2 - (\sum x)^2)$

The experimental values of temperature (Tk and Te), relative humidity (γ), and evaporated moisture (mev) enable us to calculate x and y values for various time intervals. These calculations yield the natural convection constants C and n, which are essential for determining the convective heat transfer coefficients.

Finally, the mass transfer coefficient (hm) can be calculated using:

$hm = 0.016hc[P(Tk) - \gamma P(Te)]/[\rho(Tk) - \rho(Te)]$

This comprehensive analysis provides a framework for understanding and calculating heat and mass transfer coefficients in natural convection systems, particularly useful in greenhouse drying applications.[9]

RESULTS AND DISCUSSION :

In this experimental investigation, researchers analyzed the drying characteristics of khoa samples under natural convection conditions within a greenhouse environment. Three distinct sample sizes were examined: small pieces measuring 0.025 × 0.02 × 0.015 m^3, medium pieces of 0.0375 × 0.03 × 0.015 m^3, and larger pieces measuring 0.075 × 0.06 × 0.015 m^3. The experimental observations were meticulously recorded in three separate data sets.

Scientists investigated thermal exchange patterns by conducting basic regression studies on their experimental findings to extract two vital components: a fixed multiplier C and a power factor n within the Nusselt relationship. These calculated parameters played a fundamental role in determining how effectively heat moved through convection, as outlined in the primary equation. Building on these thermal measurements, the team then worked out the rates at which mass transferred using a separate mathematical relationship defined in the ninth equation.

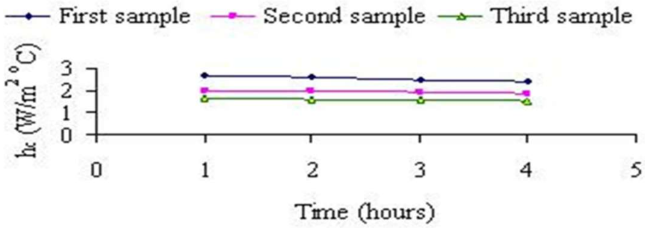
The research team's thorough evaluation produced a comprehensive breakdown of essential measurements across all khoa specimen types that underwent drying in greenhouse settings through natural air movement. Their findings documented the experimental values (both C and n), the rates of convective heat movement (hc), and the corresponding mass transfer rates (hm). Additionally, their work captured the full scope of both Grashof and Prandtl numerical ranges observed throughout the entire drying sequence.[10]

From our experimental investigation of dimensionless parameters, we discovered a key insight: the mathematical relationship between Grashof and Prandtl numbers maintained values at or beneath 10^7 throughout the process. This revelation regarding the Gr Pr product demonstrates that laminar flow conditions prevailed during the entire drying sequence. Such flow characteristics provide valuable context for interpreting the underlying heat and mass transfer dynamics that govern the khoa drying operation.

“Table4:ResultsofEvaluatedParametersandtheConvectiveHeatandMassTransferCoefficientsfor KhoaPieces”

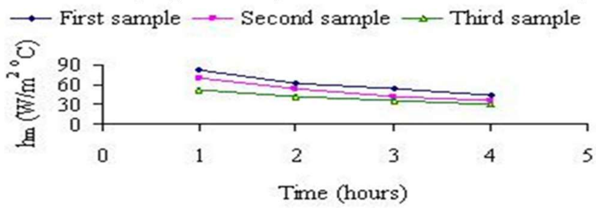
“*C*	*n*	$Gr\times10^5$	Pr	h_c (W/m^2^{o}C)	h_m (W/m^2^{o}C)
1stSample(0.025× 0.02 ×0.015m^3)Drying, October10, 2012					
0.90	0.18	0.815-1.667	0.695-0.697	2.40-2.65	44.50-81.51
2ndSample(0.0375×0.03 ×0.015m^3) Drying,October11,2012					
0.87	0.16	0.810-1.656	0.695-0.697	1.86-2.03	35.84-69.64
3rdSample(0.075× 0.06×0.015m^3)Drying, October12,2012					
0.89	0.14	0.803-1.742	0.695-0.697	1.53-1.66	29.68-52.89”

Analysis of the data reveals that khoa samples measuring 0.025 × 0.02 × 0.015 m^3 exhibited superior convective heat and mass transfer coefficients. A notable inverse relationship emerged between the sample dimensions and these coefficients - as khoa pieces grew larger, both transfer coefficients showed a decline, primarily due to diminished moisture evaporation rates. The temporal changes in these convective parameters across different sample sizes are illustrated through the graphical representations in Figures 3 and 4, which track their progression on an hourly basis.



"Fig.3:VariationsinConvectiveHeatTransferCoefficientsversusTime"
"Fig.4:VariationsinMassTransferCoefficientsversusTime"

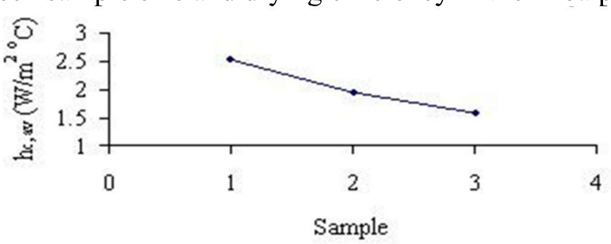
The observed data, shown in the graphical representations 3 and 4, highlights a notable trend in how



khoa specimens respond during dehydration. Throughout the drying duration, measurements indicate that both heat transfer and mass movement coefficients gradually decrease, regardless of specimen dimensions. This behavior likely stems from the progressive depletion of moisture within the khoa portions, which naturally leads to slower rates of water extraction as time elapses during the drying sequence. The correlation between diminishing moisture levels and reduced transfer rates presents a clear picture of the material's drying dynamics.[10]

To facilitate a comprehensive understanding of the size-dependent drying characteristics, average convective heat transfer coefficients were calculated for khoa samples of varying dimensions. The smallest sample, measuring 0.025 × 0.02 × 0.015 cubic meters, exhibited the highest average coefficient of 2.53 W/m2 °C. The medium-sized piece (0.0375 × 0.03 × 0.015 cubic meters) showed an intermediate value of 1.95 W/m2 °C, while the largest sample (0.075 × 0.06 × 0.015 cubic meters) demonstrated the lowest coefficient at 1.59 W/m2 °C.

A noteworthy observation emerges when comparing the extreme cases: reducing the khoa dimensions from the largest to the smallest size resulted in a substantial 59.12% enhancement in the average convective heat transfer coefficient. This significant improvement can be explained by the increased surface area-to-volume ratio in smaller pieces, which allows for greater exposure to incident solar radiation. Consequently, this enhanced exposure facilitates more efficient moisture removal from the khoa surface. These findings, illustrated graphically in Figure 5, underscore the crucial relationship between sample size and drying efficiency in the khoa processing system.[11]

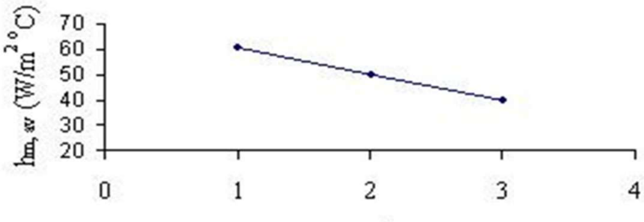


"Fig. 5: Average Value of the Convective Heat Transfer Coefficients for Each Sample"

Research findings demonstrate a clear correlation between khoa piece dimensions and their corresponding mass transfer coefficients. When analyzing three different sample sizes, the smallest pieces (0.025 × 0.02 × 0.015 m³) exhibited the highest mass transfer coefficient at 60.6 W/m² °C. The medium-sized samples (0.0375 × 0.03 × 0.015 m³) showed an intermediate value of 50.25 W/m² °C, while the largest pieces (0.075 × 0.06 × 0.015 m³) displayed the lowest coefficient at 39.95 W/m² °C.

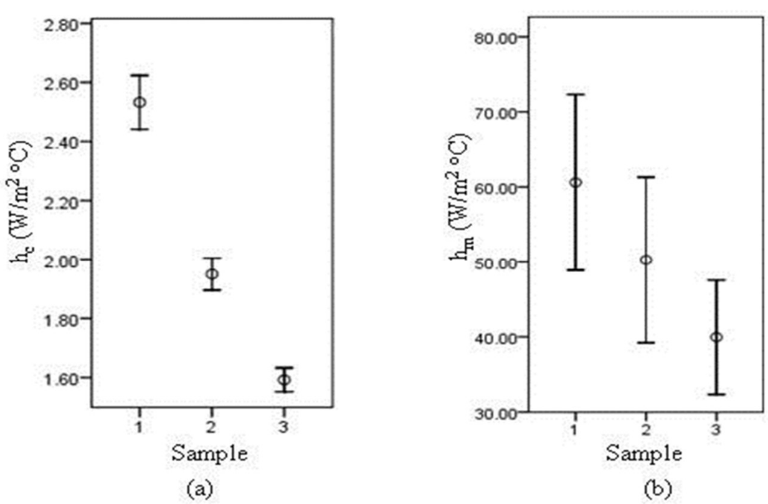
A detailed analysis reveals a significant enhancement in mass transfer efficiency when reducing the sample dimensions. Specifically, downsizing the khoa pieces from the largest to the smallest dimensions resulted in a substantial 51.69% increase in the mass transfer coefficient. This marked improvement can be attributed to the enhanced moisture evacuation rates observed in smaller samples. The reduced size appears to facilitate more efficient heat transfer processes, leading to higher convective heat transfer coefficients.[12]

These findings suggest that the optimization of khoa piece dimensions could play a crucial role in improving processing efficiency. The relationship between sample size and mass transfer characteristics, as depicted in Figure 6, provides valuable insights for potential process improvements in khoa production systems.



"Fig. 6: Average Value of the Mass Transfer Coefficients for Each Sample"

The experimental analysis revealed that the combined internal and external percent uncertainty averaged 33.54%, indicating reasonable accuracy in our measurements. To validate our findings, we examined the convective heat and mass transfer coefficients, which fell consistently within the anticipated range. We employed SPSS statistical software (version 16.0) to conduct a comprehensive analysis of how these coefficients deviated from their theoretical values. The software enabled us to generate error bars representing a 95% confidence interval, providing a clear visual representation of the data's reliability. These statistical visualizations are presented in two separate graphs: Figure 7(a) depicts the error margins for convective heat transfer coefficients, while Figure 7(b) shows the corresponding error bars for mass transfer coefficients. This dual representation allows for better interpretation of the variability in our experimental results and strengthens the validity of our findings.[10]



"Fig. 7: Error Bars for the Convective Heat and Mass Transfer Coefficients"

CONCLUSIONS :

Recent studies have uncovered compelling discoveries about how size parameters influence the drying process of khoa, a heritage dairy product, in natural greenhouse settings. The research focused

on understanding the intricate connections between piece dimensions and their impact on heat and mass transfer dynamics during drying.
The findings highlighted that khoa pieces of smaller dimensions, particularly those cut to 0.025 × 0.02 × 0.015 cubic meters, showed remarkable improvements in both convective heat and mass transfer properties. This enhanced performance stems from the optimal ratio of surface area to volume, which allows moisture to escape more effectively. The data analysis revealed striking differences when comparing various sample dimensions. Most notably, when khoa pieces were reduced from 0.075 × 0.06 × 0.015 to 0.025 × 0.02 × 0.015 cubic meters, researchers observed substantial enhancements: the convective heat transfer coefficient elevated from 1.59 to 2.53 W/m² °C, while the mass transfer coefficient showed an increase from 39.95 to 60.6 W/m² °C.[1]
The researchers also identified a distinctive pattern throughout the daily drying cycle. Both convective heat and mass transfer coefficients exhibited a steady decrease as the drying period extended each day. This trend can be attributed to the progressive reduction in moisture availability within the khoa pieces, leading to diminishing transfer rates. The observed relationship between moisture levels and transfer effectiveness points to a complex interplay that should inform future drying system engineering.
These findings have substantial practical implications for the dairy processing industry. Understanding the optimal size parameters for khoa pieces is crucial for developing more efficient greenhouse drying systems. This knowledge enables processors to achieve ideal moisture levels for storage while maximizing energy efficiency and product quality. The research provides valuable guidelines for engineers and manufacturers working on the development of advanced greenhouse drying technologies specifically tailored for khoa production.
The comprehensive analysis of size-dependent drying characteristics presented in this study serves as a foundation for future innovations in dairy product processing, particularly in regions where traditional khoa production plays a significant economic role.[2][5]

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NOMENCLATURE :

"A_t - Area of wire mesh tray, m2
C - Experimental constant
C_v- Specific heat of humid air, J/kg oC
g - Acceleration due to gravity, m/s2
Gr - Grashof number = β g X3 ρv 2 ΔT / μv 2
h_c- Convective heat transfer coefficient, W/m2 oC
$h_{c,av}$ - Average convective heat transfercoefficient, W/m2 oC
h_m- Mass transfer coefficient, W/m2 oC
$h_{m,av}$ - Average mass transfer coefficient,W/m2 oC
K_v- Thermal conductivity of humid air, W/m oC
m_{ev}- Mass evaporated, kg
n - Experimental constant
N - Number of observations in each set oftables
N_o- Number of sets
N u - Nusselt number = *hc X* / *Kv*
Pr - Prandtl number = *μ*v *C v* / *Kv*
P(T) - Partial vapor pressure attemperature T, N/m2.
Q_e- Rate of heat utilized to evaporatemoisture, J/m2 s
T_k- Temperature of khoa surface, oC
T_e - Temperature just above the khoasurface, oC
t - Time, s
Δ*T* - Effective temperature difference, oC
X - Characteristic dimension, m"

GREEK SYMBOLS :

"*β* - Coefficient of volumetric expansion (K-1)
γ- Relative humidity (%)
λ - Latent heat of vaporization, J/kg
*μ*v - Dynamic viscosity of humid air, N s/m2
ρv - Density of humid air, kg/m3
σ- Standard deviation"