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Enhancing fish drying efficiency and quality: A comparative study of intermittent microwave convective drying (IMCD) and conventional methods

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ABSTRACT

Microwave (MW) heating offers a unique drying mechanism which pushes internal moisture to the surface during the drying of water-rich foods including fish. However, the continuous application of MW energy causes excessive localized heating, resulting in the deterioration of food quality. Although intermittent microwave convective drying (IMCD) is recognized as an advanced drying technology that addresses the limitations of conventional microwave, convective, and combined microwave convective drying methods, its practical application remains limited. Notably, there is inadequate research on the use of IMCD for fish drying. This study addresses this critical gap by investigating the effects of microwave intermittency on drying kinetics, energy consumption, and key quality attributes of fish, including shrinkage, rehydration capacity and visual appearance. Convective drying (CD), microwave convective drying (CMW) drying and IMCD, was conducted to compare the drying kinetics energy consumption and quality of dried fish fillet. It was found that IMCD took only 12 min to complete the drying process, whereas CD took approximately 300 min. IMCD provided achieved better, dried fish samples achieved superior quality, drying time was reduced by 90 % and energy consumption was reduced by 20 % in comparison with convective drying. Moreover, pattern of shrinkage, changes of colour, uniformity of colour, rehydration capasity are found better in the IMCD dried fish sample. These findings clearly establish IMCD as the best drying method for fish drying particularly at industry level. MW drying takes around 10–20 times less time than convective drying to remove the same quantity of moisture. IMCD exhibits an exergy efficiency of 23.84 %, which is higher than convective drying (14.99 %) and closer to CMW drying (21.45 %). This indicates that IMCD has a more efficient utilization of energy for useful work output. The appearance and protein content properties of the IMCD dried fish fillet appeared better than those of CD and CMW dried samples. Furthermore, the least shrinkage and superior rehydration capacity were observed in IMCD dried samples. This study also identifies the need for further optimization and integration of real-time monitoring technologies to enhance energy efficiency and product quality, highlighting the broader industrial relevance and future development potential of IMCD in fish drying applications.

1. Introduction

Fish is well known for its various nutritional compositions and contains easily digestible protein, rich in omega 3 PUFAs, rich in numerous macro and micro minerals (Shahriar et al., 2022). Drying is one of the widely used preservation techniques which minimizes microorganism growth and inactivates enzymes (Duan et al., 2004; Bala and Mondol, 2001; Bellagha et al., 2002). Due to high moisture content, fish is highly venerable in propagation of microorganisms than plant-based food materials. Both bacteria and enzyme of fish activate more than plant-based food materials at same temperature. In addition to this, highly unsaturated fats present in fish make it more susceptible to microorganism growth and oxidation.

Traditional fish preservation methods like sun drying, solar drying, and hot air drying are commonly used, but they have several limitations despite their popularity. While they are relatively inexpensive and straightforward to execute, they are often not the most efficient choices

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Nomenclature

CD	Convective Drying-
CMW	Continuous Microwave -
IMCD	Intermittent microwave convective drying–
ΔE or $\boldsymbol{\Delta E_{RGB}}$	Total color change –
MC (db)	Moisture content (dry basis) g/g
$\boldsymbol{M_e}$	Equilibrium moisture content g/g
$\dot{m}$	Mass flow rate of air kg/s
M0	Initial moisture content g/g
SEC	Specific energy consumption kJ/kg
T	Temperature °C
$\boldsymbol{D_{eff}}$	effective moisture diffusivity m^2/s
PR	Pulse Ratio -
MR	Moisture ratio -
VR	Volume ratio -
RR	Rehydration Rato -
$\boldsymbol{\eta_{Ex}}$	Exergy efficiency -
$\boldsymbol{\eta_{en}}$	Energy efficiency -

(El-Mesery et al., 2024; Kumar et al., 2014). Conventional hot air drying, a method known for its slow pace and limited energy efficiency, often leads to steep temperature gradients within the food, with the surface experiencing the highest temperatures that gradually decrease towards the inner layers (Bellagha et al., 2002). Moreover, fish, being high in fat and protein content, are particularly vulnerable to degradation when subjected to extended periods of heat during conventional drying processes. This degradation can lead to a loss of essential nutrients, further highlighting the inadequacy of current fish drying technologies (El-Mesery et al., 2024).

Hybrid drying technologies are essential for improving the efficiency and quality of food drying processes, especially where conventional convective drying falls short. Convective drying alone often results in long drying times, uneven moisture distribution, and quality degradation. To overcome these challenges, hybrid methods such as microwave convective drying and infrared hot air drying (IR-HAD) have been developed (El-Mesery et al., 2024; Kumar et al., 2014). These techniques combine traditional hot air drying with microwave or infrared energy to accelerate drying, enhance energy efficiency, and better preserve the nutritional and sensory qualities of the product (El-Mesery et al., 2024; Joardder and Karim, 2022). Such innovations are particularly valuable in high-quality food processing, including fish drying.

In hot air microwave drying, microwave energy is employed in conjunction with the flow of hot air over the drying samples. This combination enables internal moisture to transfer faster towards the surface, facilitating its removal by the hot air flow to surrounding. By enhancing heat transfer rates through forced convection, this approach effectively reduces drying times. By combining the strengths of both drying techniques, researchers have been able to achieve notable improvements in the texture, flavor, and overall quality of dried fish (Zhang and Datta, 2005). This hybrid microwave-convective drying method helps us better understand how to dry fish in a more cost-effective way (Viji et al., 2019; Wang et al., 2019; Liu et al., 2018).

Qin et al. (Li et al) observed quality changes in grass carp fillets with varying microwave drying times, determining 6 min to be the optimal continuous MW drying. When heating tilapia fillets using hot air microwave drying. Duan et al. (Duan et al., 2011) found that lower hot air temperatures and microwave power levels resulted in superior quality fillets. Moreover, Argyropoulos et al. (Argyropoulos et al., 2011) proposed combined drying using hot air and microwave vacuum techniques, which demonstrated superior product quality compared to conventional hot air drying.

However, it's important to note that while hybrid microwave (MW) drying methods have shown promising results, concerns still linger regarding the uniformity of temperature distribution within the fish samples (Kumar et al., 2014). The continuous application of microwave energy during convective drying processes raises valid concerns about potential hotspots and uneven heating, which could ultimately impact the quality and consistency of the dried fish (Shahriar et al., 2022). These concerns underscore the need for further research and innovation in the realm of fish drying technologies. Despite the progress made with hybrid MW drying methods, there is still room for refinement and optimization to ensure consistent and high-quality results across different drying conditions and fish species.

The intermittent application of microwave (IMCD) energy, a well-established technique in the drying of plant-based foods, holds promise as a potential solution to the challenges encountered in fish drying processes. By carefully adjusting the frequency, duration, and intensity of microwave exposure in IMCD, researchers aimed to find the best drying conditions that remove moisture efficiently while keeping the fish's nutrients and taste intact. Despite its proven effectiveness in other food drying applications, IMCD has yet to be explored in the context of fish preservation (Shahriar et al., 2022; Joardder et al., 2023).

This study addresses a gap in current research by evaluating the feasibility and effectiveness of IMCD for drying fish. A set of experiments were carried out to analyze drying behavior, product quality, and energy consumption associated with IMCD. The results were then compared with those from conventional methods convective drying and CMW drying to highlight the strengths and weaknesses of each technique. Key performance indicators included drying rate, shrinkage, rehydration capacity, and protein retention.

2. Materials and methods

2.1. Sample preparation

Fresh specimens of *Pangasius hypophthalmus*, commonly known as pangas, were carefully sourced from a local market and promptly transported to the laboratory ensuring the freshness. Upon arrival, stringent hygiene protocols were observed to preserve the quality of the fish. Each fish specimen underwent a thorough washing process using clean tap water to remove any surface impurities and contaminants. Following the washing process, the fish was delicately filleted and into uniform rectangular shapes with the dimension of 25 mm x 50 mm x 10 mm, with each fillet weighing approximately 3–4 g.

2.2. Experimental methodology

In this study, we developed an IMCD system made to our research objectives. At the core of the setup, a 1050 W domestic microwave oven was modified to serve as the microwave energy source. To enhance the system's performance, we incorporated several modifications, including the addition of an electric resistance heater to supply hot air within the drying chamber. The internal dimensions of the microwave chamber measured 520 mm x 450 mm x 210 mm, providing sufficient space for the experimental requirements. A key improvement was the addition of a perforated sheet at the rear of the microwave, allowing hot air from an external convective dryer to flow into the chamber. This ensured consistent and controlled drying conditions throughout the process. Drying experiments were carried out on a clear, sunny day, with ambient conditions of (26 ± 3) °C temperature and (63 ± 5) % relative humidity. The air velocity was consistently maintained at (1 ± 0.2) m/s for both the IMCD system and the conventional convective dryer (CD). To comply with safety standards, microwave emissions were closely monitored using a high-precision detector (Model: HT-M2, Measuring range: 0–9.99 mW/cm^2, China). Measurements consistently showed that microwave levels remained far below 5 mW/cm^2 at a distance of 5 cm from the oven surface. These results confirm the absence of hazardous microwave leakage, ensuring the safety of both the experimental setup and personnel.

A key feature of the IMCD system is the automated intermittent control of microwave power, managed by a programmable logic controller (PLC). This enables precise adjustment of the microwave ON-time at set intervals, enhancing drying efficiency and effectiveness. To promote uniform microwave energy distribution, a glass turntable was continuously rotated, ensuring even exposure of the sample to the heat source. Fig. 1 presents a schematic diagram of the IMCD setup, illustrating the integration of its components for smooth operation and controlled experimentation. Pangas fillets were subjected to IMCD at pulse ratios of 3, 4, and 5.

The pulse ratios (PR) is usually defined by the following Equation (Argyropoulos et al., 2011).

$$PR = \frac{\text{Microwave}_{\text{on time}} + \text{Microwave}_{\text{off time}}}{\text{Microwave}_{\text{on time}}} \tag{1}$$

The experiments included exploring the effect of different temperatures and pulse ratios. After conducting numerous trial-and-error experiments, it was discovered that superior quality and faster drying were attained by operating the microwave at different PR, for instance, 4 s ON and 16 s OFF of MW is referred as PR 5.

The selection of pulse ratios (PR) in this study is grounded in comprehensive physics-based mathematical modelling. The mathematical modelling details can be found in Joardder et.al (Joardder and Karim, 2022; Joardder et al., 2021; Joardder and Karim, 2023) . To justify the appropriate PR, we have included a detailed comparison of maximum temperature, average temperature, and coefficient of variation during IMCD at different PRs from physics based numerical model, alongside those observed in conventional convective drying (Fig. 2).

Throughout the drying process, the microwave power during the ON periods remained constant at 1050 W, while the OFF periods had zero microwave power, corresponding to the system's pulsed operation. A convective hot air dryer was employed for the hot air drying (CD) process. The concept of IMCD has been illustarted in Fig. 2. To compare the results of IMCD with a convective dryer, we ran the convective dryer at 60 °C. We selected this temperature for the convective dryer because it closely aligns with the temperature that IMCD most frequently reaches. This ensures a fair comparison between the two drying methods.

2.3. Measurements of properties and qualities

2.3.1. Moisture content determination

Moisture content can be expressed as the quantitative amount of water present in a food sample on a wet or dry basis. Moisture content on a dry basis is defined as the mass of water exists per unit mass of dry food materials. Using the following equation, moisture content on a dry basis has been determined (Joardder and Mourshed; Joardder et al., 2014). Using a load cell, real-time mass measurements were acquired to calculate the moisture content of the samples.

$$Moisture\ content(db) = \frac{weight_{wet} - weight_{dry}}{weight_{dry}} \tag{2}$$

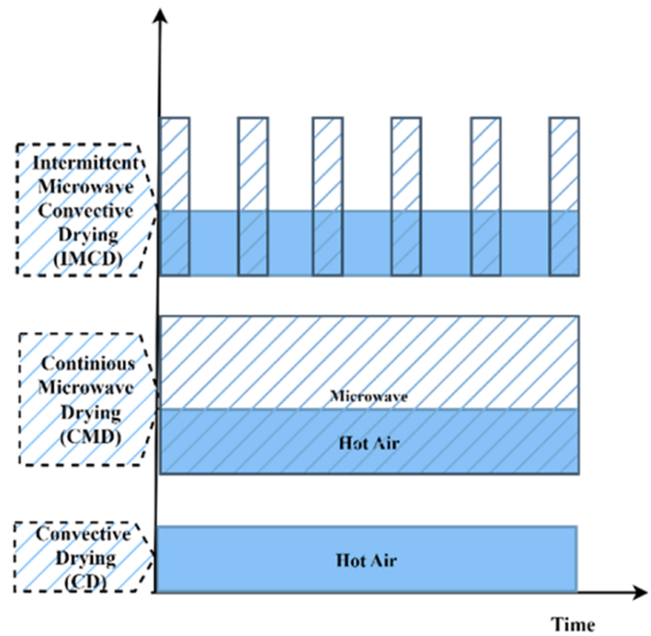


Fig. 2. Hot air and Microwave applications application strategies in CD, CMW drying and IMCD.

The initial moisture content of the *Pangasius* fillet samples used in this study was 77.5 % (wet basis), equivalent to approximately 3.44 g water/g dry matter (dry basis). This value is consistent with previously reported data for this species (Hassan et al., 2019).

2.3.2. Effective moisture diffusivity

Fick's second law of diffusion was used to express the diffusion mass transfer phenomena determined by moisture concentration gradient. Fick's second law is expressed by the following equation (Joardder et al., 2021):

$$\frac{\partial \text{MR}}{\partial \text{t}} = \nabla\left[\text{D}_{\text{eff}}(\nabla \text{MR})\right] \tag{3}$$

Here, the moisture ratio is denoted by MR, t is drying time in seconds, and the effective moisture diffusivity is denoted by D_{eff}. The moisture ratio (MR) is calculated according to the crank equation as:

$$\text{MR} = \frac{\text{M}_\text{t} - \text{M}_\text{e}}{\text{M}_0 - \text{M}_\text{e}} = \frac{8}{\pi^2}\sum_{n=1}^{\infty}\frac{1}{(2\text{n}-1)^2}\exp\left(-\frac{(2\text{n}-1)^2\pi^2\text{D}_{\text{eff}}}{4\text{L}^2}\right)\text{t} \tag{4}$$

M_0, and M_e are initial and equilibrium moisture content, respectively. The moisture contents were measured in (g/g db) and L represents the sample thickness (m). The equilibrium moisture content, M_e becomes

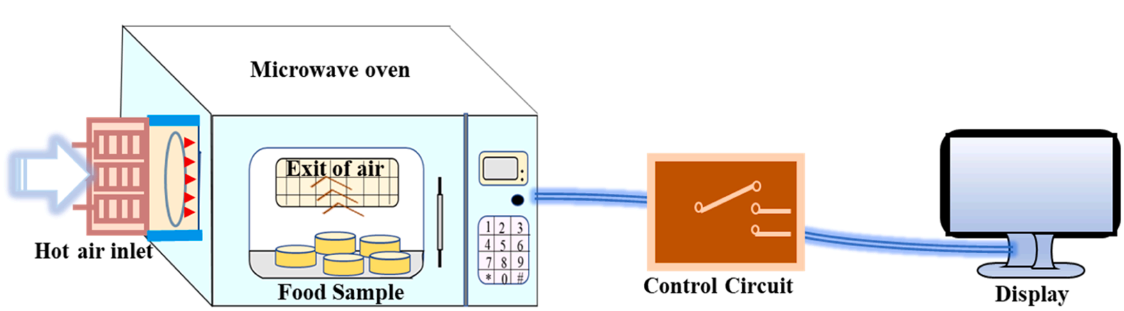


Fig. 1. Schematic diagram of the IMCD experimental setup.

negligible and only the first term of the series solution is considered for longer drying times. Thus, Eq. (3) becomes:

$$MR = \frac{M_t}{M_0} = \frac{8}{\pi^2}\exp\left(-\frac{\pi^2 D_{eff}}{4L^2}t\right) \tag{5}$$

Taking the ln of both sides of Eq. 4a gives:

$$\ln(MR) = \ln\left(\frac{8}{\pi^2}\right) - \left(\frac{\pi^2 D_{eff}}{4L^2}t\right) \tag{6}$$

The following equation represents the slope of the straight line obtained by plotting ln (MR) versus time:

$$Slope = \frac{\pi^2 D_{eff}}{4L^2} = K \tag{7}$$

The slope (K) can be obtained from the plot of $\ln\left(\frac{M-M_e}{M_o-M_e}\right)$ versus time (t). From the slope, the effective moisture diffusivity can be calculated.

As effective moisture diffusivity is influenced by various factors such as temperature, material properties, and drying method, we will determine D_{eff} for CD, CMW Drying and IMCD. The different value of D_{eff} in different drying method being will demonstrate the behavior of moisture movement within the material in the particular drying condition.

2.3.3. Image acquisition and colour analysis

Colour is an essential sensory attribute that indicates a change from the fresh product. Therefore, it is a necessary parameter to determine the appeal of the final product. An eight-megapixel digital camera was employed to capture and store high-resolution images of the samples throughout the drying process. For colour analysis, the two primary parameters considered are colour change and the colour profile, which represents the uniformity of colour distribution across the sample. To determine the colourimetric values of the fish samples, ImageJ software (NIH, USA) along with the Pixie plugin was used. This software provides numerical values for the intensity of red (R), green (G), and blue (B) light reflected or transmitted by the sample. The colour changes was determined using the following equation (Joardder et al., 2013).

The colour change in the samples throughout drying is represented by ΔE_{RGB} which can be calculated from the following equation

$$\Delta E_{RGB} = \sqrt{\left[(R_0 - R)^2 + (G_0 - G)^2 + (B_0 - B)^2\right]} \tag{8}$$

Where R_0, G_0, B_0 values correspond to the fresh samples and R, G, B to dry ones.

2.3.4. Shrinkage measurement

Shrinkage is caused due to the migration of water from the food sample throughout the drying. Thus, both volume and moisture ratio are considered to compare the relative shrinkage. Volume ratio (VR) is calculated from the following equation (Joardder and Karim, 2019):

$$VR = \frac{V_t}{V_0} \tag{9}$$

Where, V_t (cm^3) is the sample volume at any time t and V_0 (cm^3) is the initial sample volume. A digital slide caliper was used to measure the parameters essential to calculate volume. The average value of several measurements was done to mitigate the impact of irregular deformation.

2.3.5. Rehydration calculation

Rehydration is a critical parameter for assessing the quality of the final product. Products that undergo structural damage, such as the collapse of their porous matrix during drying, typically exhibit poor rehydration characteristics (Joardder et al., 2015). Rehydration was carried out by immersing a pre-weighed dried sample in distilled water maintained at 100 °C. At predetermined time intervals, the samples were removed, gently wiped with tissue paper to eliminate surface moisture, and then weighed using a digital balance. This process was repeated to monitor the rehydration kinetics over time. Rehydration ratio (RR) in percentage is calculated by the following equation (Dehghannya et al., 2018):

$$RR = \frac{m_{rh}}{m_{dh}} \times 100 \tag{11}$$

Where, m_{rh} is the mass of rehydrated sample and m_{dh} is the mass of dried product.

2.3.6. Energy and exergy analysis

Convective drying (CD): Exergy analysis determines energy availability at various spots in a system which defines energy utilization and losses. Exergy analysis offers a comprehensive framework for evaluating and optimizing drying methods from multiple perspectives, including efficiency, quality, environmental impact, and economic feasibility. In accordance with the second law of thermodynamics, a fraction of entering exergy of an irreversible thermal system with different energy sources is wasted. The data of exergy at different steady state spot and parametric exergy analysis in drying chamber were performed. The following common form of exergy equation for steady-state system was utilized (Castro et al., 2018).

$$\dot{Ex} = \dot{m}C_{pda}\left[(T - T_0) - T_0\ln\frac{T}{T_0}\right] \tag{12}$$

Where, $\dot{Ex}$(kJ/s) is exergy, $\dot{m}$(kg/s) is mass flow rate of air, C_{pda}(J/kg k) is air specific heat capacity, T(k) is temperature.

The flow rate of air mass $\dot{m}$ was determined using the following formula:

$$\dot{m} = \rho_a V_a A_{dc} \tag{13}$$

Where, ρ_a(kg/m^3) is specific mass of air, V_a(m/s) velocity of air, A_{dc}(m^2) is area of drying chamber.The following formula was used to determine inlet and outlet drying air specific heat capacities (C_{pda}) (Nazghelichi et al., 2010):

$$C_{pda} = 1.004 + 1.88w \tag{14}$$

Afterward the loss of exergy is measured considering the bellow expression:

$$\text{Exergy loss} = \text{Exergy inflow} - \text{Exergy outflow} \tag{16}$$

The inflow of exergy to drying chamber is determined by following expression:

$$\dot{Ex}_{dci} = \dot{m}_{da}C_{pda}\left[(T_{dci} - T_0) - T_0\ln\frac{T_{dci}}{T_0}\right] \tag{17}$$

The outflow of exergy from chamber is expressed through following equation:

$$\dot{Ex}_{dco} = \dot{m}_{da}C_{pda}\left[(T_{dco} - T_0) - T_0\ln\frac{T_{dco}}{T_0}\right] \tag{18}$$

The exergy due to evaporation of product can be expressed as follows (Sarker et al., 2015).

$$\dot{Ex}_{eva} = \left[1 - \frac{T_0}{T_P}\right]\dot{Q}_{eva} \tag{19}$$

$$\dot{Q}_{eva} = h_{fg}\ \dot{m}_{eva} \tag{20}$$

Where, h_{fg}(kJ/kg) is latent heat of vaporization of water.

The ratio of exergy utilized for drying product to flow of exergy to drying chamber is known as exergy efficiency and the mathematical expression is shown below.

$$\eta_{Ex} = \frac{\dot{Ex}_{dci} - \dot{Ex}_L}{\dot{Ex}_{dci}} = 1 - \frac{\dot{Ex}_L}{\dot{Ex}_{dci}} \tag{21}$$

The convective drying process exergy efficiency can be expressed by following equation (Icier et al., 2010).

$$\eta_{Ex\,pr} = \frac{\dot{Ex}_{eva}}{\dot{Ex}_{dci}} \tag{22}$$

Exergy analysis of microwave drying: The expression for changing exergy in microwave chamber is stated as (Icier et al., 2010).

$$EX_{in} = EX_{abs} + EX_{ref} + EX_{tra} \tag{23}$$

The following formula is used to calculate the microwave dryer input exergy:

$$\mathrm{P_{in}} \times t = \left((m \times \mathrm{ex})_{\mathrm{dp}} - (m \times \mathrm{ex})_{\mathrm{wp}}\right) + \mathrm{ex}'_{\mathrm{exap}} \times t + \mathrm{EX_{ref}} + \mathrm{EX_{tra}} \tag{24}$$

Where, $\mathrm{P_{in}}$(W) is the microwave power emitted by magnetron, t(s) is time, m(kg) is mass.

The exergy rate (J/s) of the evaporation in the dryer chamber can be determined by:

$$\mathrm{ex}'_{\mathrm{exap}} = \left(1 - \frac{\mathrm{T_O}}{\mathrm{T_p}}\right) \times \dot{m}_{wv}\lambda_{\mathrm{k}} \tag{25}$$

$$\dot{\mathrm{m}}_{\mathrm{wv}} = \frac{\mathrm{m}_{t+\Delta\mathrm{t}} - \mathrm{m_t}}{\Delta \mathrm{t}} \tag{26}$$

Where, λ_{k}(J/kg) latent heat of sample. The latent heat of the cantaloupe slices can be also determined by Equation as follow.

$$\lambda_k = \lambda_{wf}(1 + 23\exp(-0.4M_t)) \tag{27}$$

The free water latent heat of vaporization (kJ/kg) was estimated by the following equation (Brooker et al., 1992).

$$\lambda_{wf} = 2503 - 2.386(T - 273) \tag{28}$$

$$C_p = 840 + 3350 \times \left(\frac{M_t}{1 + M_t}\right) \tag{29}$$

The following formula used to calculate thermal capacity which dependent on moisture content

The specific exergy (J/s) can be calculated by Equation as follow (Akpinar et al., 2006).

$$ex = C_p\left[(T - T_\infty) - T_\infty \ln\left(\frac{T}{T_\infty}\right)\right] \tag{30}$$

The exergy efficiency is the ratio of exergy utilized to dry the product to exergy inflow from energy source. The stated below equation determines MW dryer exergy efficiency (Dincer and Sahin, 2004).

$$\eta_{\mathrm{ex}} = \frac{\mathrm{EX_{abs}}}{\mathrm{P_{in}} \times t} \tag{31}$$

Exergy analysis of IMCD:

The exergy efficiency for IMCD drying process was determined using ratio of dry product exergy to the summation of total sources dryer exergy (Beigi, 2016).

$$Exergy\ efficiency = \frac{exergy\ absorption}{exergy\ input} \ldots\ldots or \ldots\frac{EX_{abs}}{EX_{in}} \tag{32}$$

Energy efficiency

The energy efficiency for convective drying can be determined using the ratio of energy from water evaporation to total energy consumed for drying product (Beigi, 2016):

$$\eta_{en,\ CD} = \frac{Q_w}{E_{total}} \tag{33}$$

Where E_{total} is:

$$E_{total} = SEC * m \tag{34}$$

The following equation is used to determine energy due to water evaporation:

$$Q_w = h_{fg} * m_v \tag{36}$$

The energy efficiency of microwave energy can be calculated using equation given bellow (Darvishi et al., 2014).

$$\eta_{en,MW} = \frac{(m \times \mathrm{ex})_{\mathrm{wp}} + \lambda_k * m_{ew}}{(m \times \mathrm{ex})_{\mathrm{dp}} + p * t} \tag{37}$$

Finally, the whole drying system efficiency was determined according to following equation (Şevik et al., 2019).

$$\eta_{en,IMCD} = \frac{\dot{\mathrm{m}}_{\mathrm{wv}} * h_{fg}}{(SEC * m) + (P_{in} * t)} \tag{38}$$

Specific energy consumption

Another parameter named specific energy consumption (SEC) was used to determine the suitability of drying process. The SEC can be defined as the amount of energy require to dry 1 kg which is determined by following equation (Kaveh et al., 2018).

$$SEC = \left(\frac{C_{pa} + C_{pv}}{V_h}\right)(T_{in} - T_0)\left(\frac{Qt}{m_v}\right) \tag{39}$$

The microwave SEC was calculated using following equation (Osae et al., 2020).

$$SEC = \frac{p_{in} * \Delta t}{m_{eva}} \tag{40}$$

The total drying system SEC was determined using the equation given bellow.

$$SEC = \frac{E_{CD} + E_{MW}}{m_W} \tag{41}$$

Where, $E_{CD}$is energy consumed by convective dryer, $E_{MW}$is energy consumed by microwave dryer.

2.3.7. Determination of energy consumption

The total energy consumption for HAD is $\mathrm{E_{HAD}}$ (kWh) which is determined from the following equation: (Joardder et al., 2014)

$$\mathrm{E_{HAD}} = \rho_a A v \mathrm{C_a} \Delta \mathrm{T} \times \mathrm{D_C} \tag{42}$$

The air density and velocity are denoted by ρ_a (kg/m^3) and v (m/s) respectively. A (m^2) is the cross-sectional area where the sample is kept. ΔT (°C) is the temperature difference between the inlet and outlet air. Specific heat is denoted by $\mathrm{C_a}$ (kJ/kg °K) and $\mathrm{D_C}$ (hour) is the total drying time for CD. For simplification of the calculation process, steady conditions were considered.

In the case of IMCD, the microwave drying is intermittent, while the convective hot air is supplied continuously throughout the drying procedure. The energy consumption for IMCD is calculated from the following equation:

$$\mathrm{E_{IMCD}} = \frac{\mathrm{P_{MW} D_{IMCD}}}{\mathrm{PR}} + \mathrm{P_H D_{IMCD}} \tag{43}$$

Where, $\mathrm{E_{IMCD}}$ (kWh) is the total energy consumption for IMCD. $\mathrm{P_{Mw}}$ (W) and pH (W) are oven and heater power, respectively. $\mathrm{D_{IMCD}}$ (hour) is the total time required for IMCD and PR is the pulse ratio. For microwave-assisted convective drying (CMW), the energy consumption is calculated from the following equation:

$$E_{MCD} = (P_{MW} + P_H) \times D_{MCD} \tag{44}$$

Where, E_{MCD} (kWh) is the total energy consumption for MCD and D_{MCD} (hour) is the total time required for MCD.

2.3.8. Uncertainty calculation

Uncertainty analysis of the experiments was done according to Chandan et al. (Kumar and Karim, 2015) If the result R of an experiment is calculated from a set of independent variables so that $R = R(X_1, X_2, X_3, \ldots, X_N)$, then the overall uncertainty can be calculated using the following expression:

$$\delta R = \left(\left(\frac{\partial R}{\partial X_1}.\delta X_1\right)^2 + (\left(\frac{\partial R}{\partial X_2}.\delta X_2\right)^2 + \ldots + \left(\frac{\partial R}{\partial X_N}.\delta X_N\right)^2\right)^{\frac{1}{2}} \tag{45}$$

and the relative uncertainty can be expressed as follows:

$$e = \frac{\delta R}{R} = \left(\left(\frac{1}{R}\frac{\partial R}{\partial X_1}.\delta X_1\right)^2 + \left(\frac{1}{R}\frac{\partial R}{\partial X_2}.\delta X_2\right)^2 + \ldots + \left(\frac{1}{R}\frac{\partial R}{\partial X_N}.\delta X_N\right)^2\right)^{\frac{1}{2}} \tag{46}$$

The relative uncertainty for a variables is expressed as the uncertainty of a measurement as a fraction (or percentage) of the measured value:

$$Relative\ Uncertainty = \frac{\delta X}{X}$$

Where: X is the measured value and δ_X is the absolute uncertainty (or error margin)

Uncertainty Analysis of Temperature

The temperature was directly obtained from the calibrated thermocouple, and the accuracy was within the American Society of Heating, Refrigerating and Air Conditioning Engineers' recommended range, which is ±0.5 °C. Therefore, the uncertainty of the temperature would be:

$$T = T_{measured} \pm 0.5^{\circ}C$$

Uncertainty Analysis of Moisture Content

The dry basis moisture content ratio of the weight of moisture, W is the weight of the sample and bone-dry weight, W_d. As W and W_d both are obtained using the same load cell, and as per the manufacturer's specification, the percentage error of the load cell is ±0.1 %; therefore, $\delta W = \delta W_d = 0.0001$. Substituting all of the values in following equation, the relative uncertainty for moisture content, em, is obtained, and the value is found to be ±1.06 %.

$$e_m = \left(\left(\frac{\delta W}{W - W_d}\right)^2 + \left(\frac{W.\delta W}{(W - W_d).W_d}\right)^2\right)^{\frac{1}{2}} = \pm 1.06\%$$

Uncertainty of energy and exergy efficiency were calculated using the combined relative uncertainty of the associate parameters.

3. Results and discussion

3.1. Temperature uniformity during different drying conditions

To evaluate the thermal behavior of samples during microwave (MW) convective drying, temperature metrics were monitored under varying MW OFF intervals and compared to conventional convective drying. The Fig. 3 below presents the maximum temperature, average temperature, and coefficient of variance (CV) of temperature over time for each treatment condition.

IMCD with varying MW OFF intervals significantly influenced the thermal behaviour of the samples. Maximum temperature profiles showed a rapid initial rise across all treatments, followed by stabilization. Samples with shorter MW OFF intervals (4 s and 8 s) reached the highest peak temperatures, often exceeding the expected maximum of 80 °C. In contrast, longer intervals (16 s and 20 s) resulted in lower peak temperatures, generally remaining below this threshold. Average temperature trends followed a similar pattern. Samples with shorter OFF intervals achieved higher average temperatures, frequently surpassing the target of 60 °C. Longer OFF intervals led to slower heating and lower average temperatures, often falling short of the desired range.

The coefficient of variance (CV) of temperature, used as an indicator of thermal uniformity, was highest in samples with shorter MW OFF intervals, indicating greater temperature variability. Conversely, longer OFF intervals and conventional convective drying exhibited lower CV values, reflecting more uniform temperature distribution. Considering both thermal targets and uniformity, MW OFF intervals of 16 s appear optimal balancing sufficient heating (approaching 60–80 °C) with improved temperature uniformity compared to shorter intervals.

Therefore, a pulse ratio of 5 (i.e., 4 s microwave ON and 16 s OFF) offers the most favorable balance, achieving more uniform temperature distribution, maintaining temperatures within an acceptable range, and enabling faster drying compared to convective drying. These findings support IMCD PR 5 as an optimal setting in this study.

3.2. Drying kinetics

The variation in moisture content over drying time for the selected fish samples under convective, CMW, and IMCD drying methods is illustrated in Figs. 4 and 5.

It is depicted from Fig. 4 that CMW drying sample requires lower energy than convective drying samples. Moisture transfer rate is faster for microwave-assisted drying because of generating more heat for

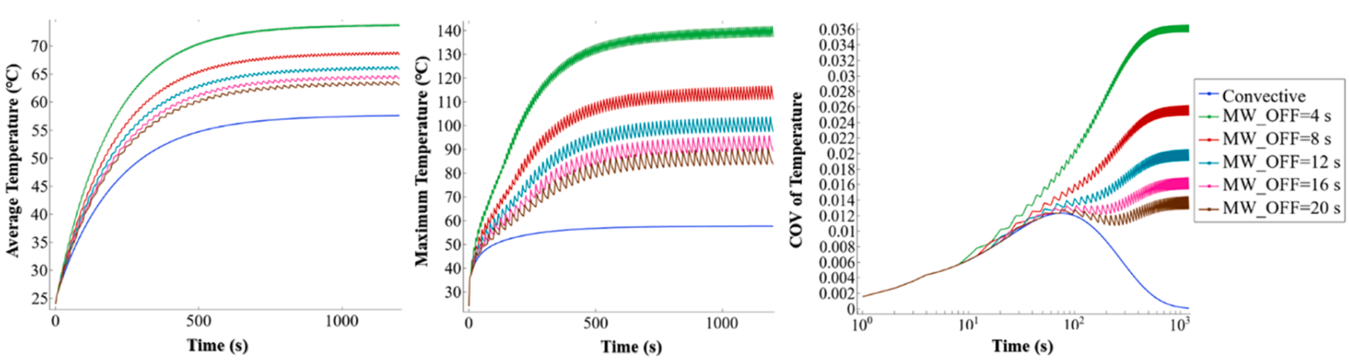


Fig. 3. Maximum temperature (left), average temperature (middle), and coefficient of variance of temperature (right) during microwave convective drying under different MW OFF intervals and conventional convective drying.

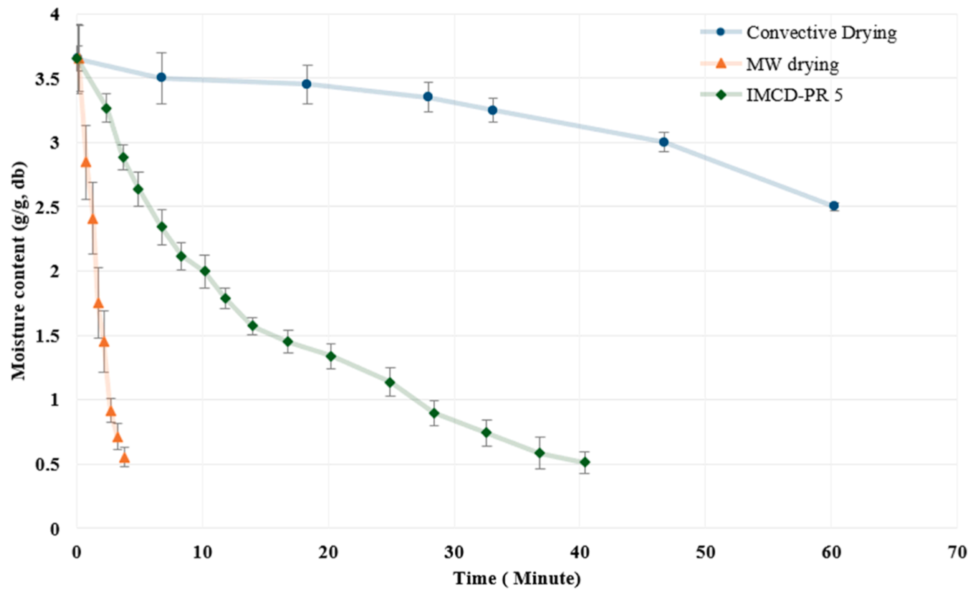


Fig. 4. Drying kinetics of Pangas fish in different drying approaches.

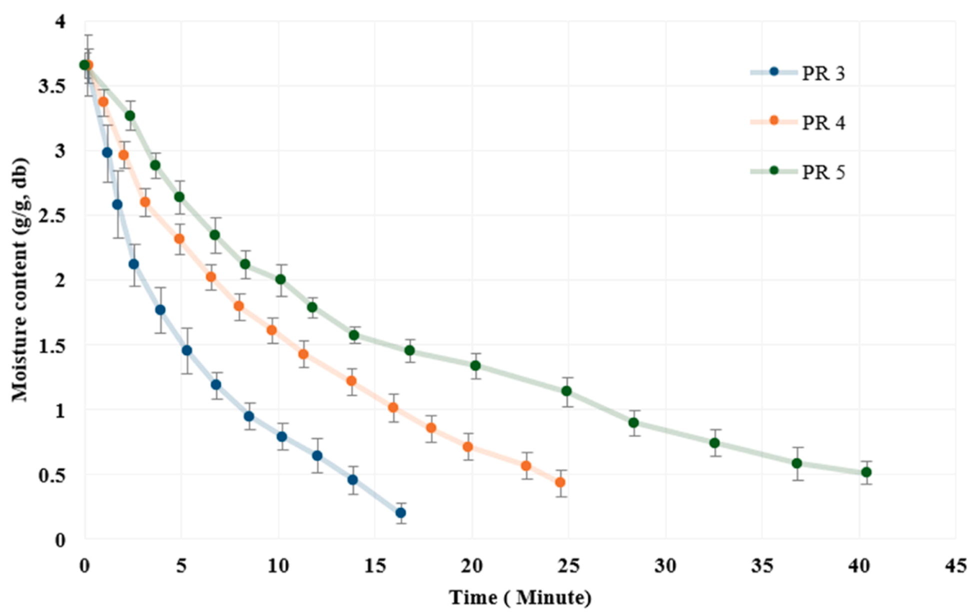


Fig. 5. IMCD drying kinetics of Pangas fish at different pulse ratios.

drying purposes. Consequently, the time required for drying is significantly lower in the case of CMW samples.

In IMCD, microwave energy induces volumetric heating through dielectric loss mechanisms, where polar water molecules oscillate in response to the alternating electromagnetic field. This results in internal heat generation, which enhances moisture migration from the interior to the surface. The intermittent nature of IMCD allows for thermal relaxation during the OFF cycles, reducing the risk of localized overheating and promoting more uniform temperature distribution (Pham et al., 2017; Masud et al., 2022). This faster moisture removing rate may be attributed to the increased evaporation of both internal and surface water of fish fillets due to the application of microwave heating. Similar drying kinetics of potato (Masud et al., 2022)apple (Joardder and Karim, 2022), kiwi (Pham et al., 2018) under IMCD has been reported in literature.

In IMCD, microwave energy induces volumetric heating through dielectric loss mechanisms, where polar water molecules oscillate in response to the alternating electromagnetic field. This results in internal heat generation, which enhances moisture migration from the interior to the surface. The intermittent nature of IMCD allows for thermal relaxation during the OFF cycles, reducing the risk of localized overheating and promoting more uniform temperature distribution (Joardder and Karim, 2022; Joardder et al., 2023; Joardder and Karim, 2023; Joardder and Mourshed; Joardder et al., 2013; Masud et al., 2022; Kumar et al., 2014; Rahman et al., 2018; Pereira et al., 2025).

In order to dry the sample to the same final moisture content, IMCD (PR 5) took a significantly longer drying time. The sample took about 5 min to reach a moisture content of 1.57 for MCD, whereas the IMCD (PR 4) required almost 16 min to reach the same moisture content. Fig. 4 is a clear expression to describe that the convective drying requires around 10 - 12 times more time than that of other types of drying for this experiment. These observations highlight the importance of considering both energy efficiency and drying time when evaluating different drying methods for preserving the quality of dried fish samples. The significantly lower drying time for MCD and IMCD samples implies that less energy is required overall for the drying process compared to convective drying methods. This is because the faster drying rate results in reduced energy consumption per unit of dried product.

3.2.1. Effective diffusivity

Drying kinetics for different drying conditions as shown in Figs. 4 and 5. From the drying curves, the effective moisture diffusivity of the samples has been calculated and presented in Table 1.

Different drying conditions facilitate mass transfer phenomena in different trends. Convective drying removes the surface water quickly, whereas it takes a significant amount of time to remove internal water. Therefore, the overall moisture diffusivity is smaller than the microwave drying. During microwave drying, internal moisture is triggered to move towards the outside, resulting in a high evaporation rate (Shahriar et al., 2022). Attaining the advantages of both convective and microwave drying, IMCD offers moderate moisture diffusivity. However, the effective diffusivity varies with the variation of PR of MW application (Table 2).

Fig. 6 presents R^2 values of model used to correlate the relationship between the natural logarithm of moisture ratio (Ln(Moisture Ratio)) and time (seconds). The R^2 values for CD and CMW both achieved 0.9966, indicating an almost perfect fit. This implies that the linear regression model for these datasets can predict the moisture ratio with high accuracy based on the time variable. Similarly, the IMCD-PR 5 shows a strong fit with an R^2 value of 0.9753, further supporting the robustness of the model.

Even the with tower R^2 values, such as PR 3 (4, 8) and PR 4 (4, 12), still exhibit strong fits with R^2 values of 0.9419 and 0.9304, respectively. These values are well above the threshold typically considered indicative of a good fit, reinforcing the credibility of the diffusivity calculations derived from these models.

The range of moisture diffusivity of food materials has been reported within the range of 10^{-11} and 10^{-6} m^2/s (Guan et al., 2013; Komolafe et al., 2018; Ortiz et al., 2013; Wang et al., 2011). More specifically, effective diffusivity of fish during convective drying can be observed within the range of 7.82×10^{-11} to 0.31×10^{-09} (Visavale et al., 2011; Toujani et al., 2013). On the other hand, it is 1.54×10^{-09} to 1.5×10^{-6} for MW drying, which is quite high (Darvishi et al., 2013; Ismail and KOCABAY, 2018) .

3.3. Energy and exergy efficiency

Table 2 illustrates the impact of varying drying system temperatures on the exergy efficiency of the CD, CMW drying, and IMCD systems. The exergy efficiency reflect the effectiveness of energy utilization across the different drying processes.

Based on the results, the exergy efficiency was determined to be 14.99 %, 21.45 %, and 23.84 % for the CD, MWD, and IMCD systems, respectively. These findings are consistent with previous studies, which reported exergy efficiencies ranging from 1.64 % to 14.43 % for fish in spray drying (Aghbashlo et al., 2012), 4.18 % to 12 % for rough rice in fluidized bed drying (Khanali et al., 2013), and 11.35 % to 24.68 % for kiwi samples in microwave drying (Darvishi et al., 2016).

Table 1
Moisture diffusivity of pangas fish of different drying conditions.

Drying condition	PR (On, Off) sec	D_{eff} (m^2/s)
Convective drying	–	2.43185×10^{-09}
Continuous MW Drying	–	4.70158×10^{-07}
IMCD, PR 5	4:6	2.43185×10^{-08}
IMCD, PR 4	4:12	5.2690×10^{-08}
IMCD, PR 5	5:20	7.29556×10^{-08}
IMCD, PR 3	4:8	9.72741×10^{-08}
IMCD, PR 3	7:14	1.54017×10^{-07}

Table 2
Energy and exergy efficiency at different drying conditions.

Drying system	Energy Efficiency (%)	Exergy Efficiency (%)	SEC (MJ/kg)
Convective Drying	13.25 ± 0.39	14.99 ± 0.33	15.50 ± 0.78
MW Drying	29.97 ± 0.87	21.45 ± 0.47	2.66 ± 0.13
IMCD	26.05 ± 0.76	23.84 ± 0.53	4.44 ± 0.22

Compared to conventional convective drying (CD), both CMW drying and IMCD show much higher exergy efficiency, meaning they use energy more effectively. While CD relies on hot air for heating, microwave drying uses thermal radiation to evaporate moisture. In IMCD, microwaves help maintain a more uniform and higher temperature throughout the product, which improves moisture removal. The higher temperature at the surface speeds up moisture movement from inside the material. Also, the interaction between microwave energy and the product boosts both heat and mass transfer, making the drying process faster. As a result, IMCD achieves better exergy efficiency than other methods due to its effective energy transfer.

In calculating uncertainty exergy analysis, the exergy input from hot air in an IMCD system was calculated using the air mass flow rate ($\dot{m_{air}}$), specific heat capacity (C_p), and temperature measurements (T_{in}, T_0). Since exergy is a function of these variables, the relative uncertainty in the calculated exergy ($\frac{\delta Ex}{Ex}$) is determined by combining the relative uncertainties of each contributing parameter. Using standard instrument accuracies, the combined relative uncertainty in energy calculation is typically around ±2.91 %. Similarly, the accuracy of exergy calculations depends on precise measurements of air mass flow rate, inlet air temperature, and ambient temperature. Using typical instrument accuracies and procedure mentioned in Section 2.3.8, the combined relative uncertainty in exergy calculation is estimated to be around ±2.21 %.

The Table 2 presents the specific energy consumption (SEC) for fish drying using different methods: CD, CMW, and IMCD. Convective drying showed the highest SEC at 15.5 MJ/kg, primarily due to its lower water removal rate. In contrast, microwave drying methods (CMW and IMCD) use thermal radiation to create temperature gradients between the heat source and the product, resulting in faster and more efficient drying. The SEC values observed in this study are consistent with those reported in the literature for conventional hot air drying techniques. The specific energy consumption (SEC) for convective drying of agricultural products shows significant variation, ranging from approximately 7 MJ/kg to as high as 267 MJ/kg, depending on the product type, slice thickness, and drying conditions (Ying and Spang, 2024; Kaveh et al., 2023). The SEC during CMW drying and IMCD recorded in this study is consistent with SEC values reported for microwave drying ranging from 1.5 to 4.5 MJ/kg, demonstrating the energy efficiency of microwave-assisted drying methods (Shahriar et al., 2022). Moreover, the combination of infrared and microwave heating with the hot air-drying method reduced the specific energy consumption (SEC) by 54.3 % and 75.3 %, respectively, compared to convective hot air drying of green peas (EL-Mesery et al., 2022; Jimoh et al., 2023).

In summery, both MWD and IMCD outperform CD in terms of exergy efficiency and specific energy consumption, with IMCD offering better drying quality and uniformity despite slightly lower energy efficiency compared to MWD.

3.4. Shrinkage

Fig. 7 illustrates the shrinkage behavior of samples dried under various conditions. A clear distinction is observed among the drying methods. Samples treated with microwave-based techniques (CMW and IMCD) exhibit reduced shrinkage, remaining below the ideal shrinkage

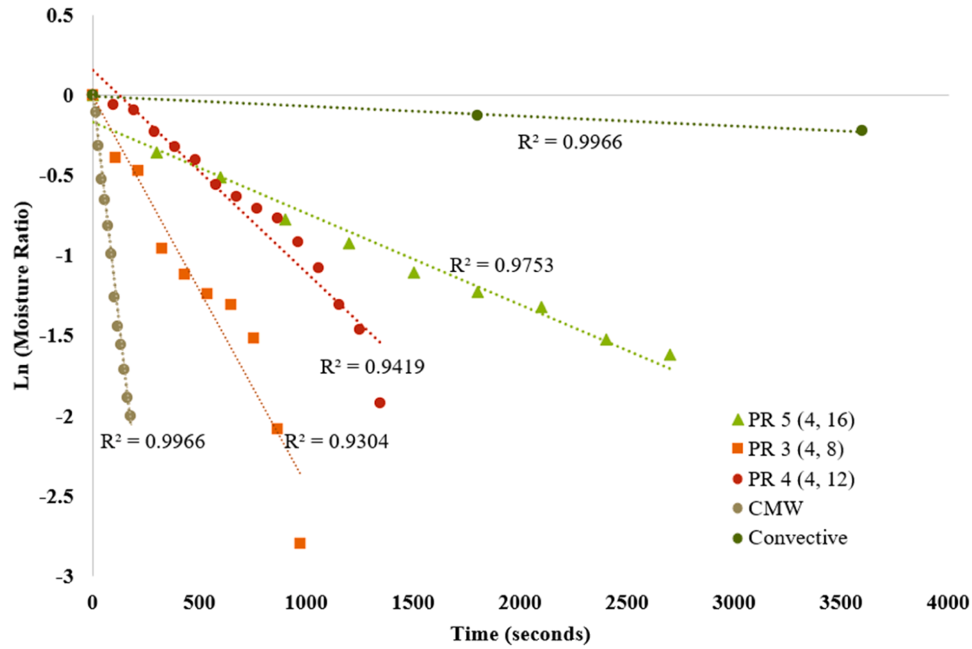


Fig. 6. Determination of Effective moisture diffusivity under different drying conditions.

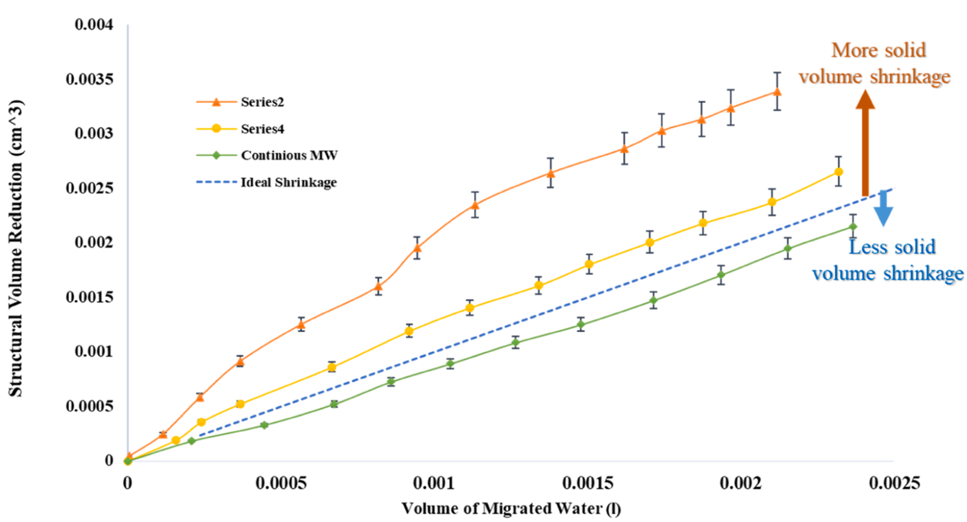


Fig. 7. Correlation between structural volume reduction and volume of water migrated.

line. In contrast, samples subjected to convective drying show greater shrinkage, deviating above the ideal line. These trends highlight the effectiveness of microwave-assisted drying in preserving the structural integrity of the samples.

Specifically, in the case of MW drying, the volume reduction is less than the volume of water removed, indicating the development of a more porous structure compared to fresh counterparts. Conversely, convective drying results in higher cell collapse, leading to maximum shrinkage. Additionally, IMCD dried samples closely approximate the ideal shrinkage, suggesting minimal collapse and expansion compared to other methods.

This observation underscores that both continuous microwave (MW) drying and intermittent microwave-convective drying (IMCD) are effective in preserving structural integrity, as indicated by their minimal deviation from ideal shrinkage. The reduction in structural volume is notably lower in IMCD compared to convective drying, indicating that IMCD-treated samples exhibit greater porosity than those subjected to convective drying. This findings align with other hybrid drying of food material (İzli and Yildiz, 2021) .These findings suggest that IMCD provides significant benefits in maintaining structural quality, particularly in applications where preserving structural integrity is essential, such as in the food industry.

3.5. Rehydration

Fig. 8 shows how the amount of moisture removed (compared to the starting weight) relates to the change in volume (final volume compared to the starting volume) for three drying methods: convective drying, continuous microwave drying, and intermittent microwave-convective drying (IMCD).

It is observed that samples dried in IMCD condition had higher values of rehydration ratio (RR) 195 %, whereas 160 % was found for CD treated samples. The higher value of RR for the IMCD treated implies that IMCD had less irreversible deformation than CD. The findings of current work are in a good agreement with those of Izli and Yildiz (İzli and Yildiz, 2021) who found lower rehydration ratios of CD carrot

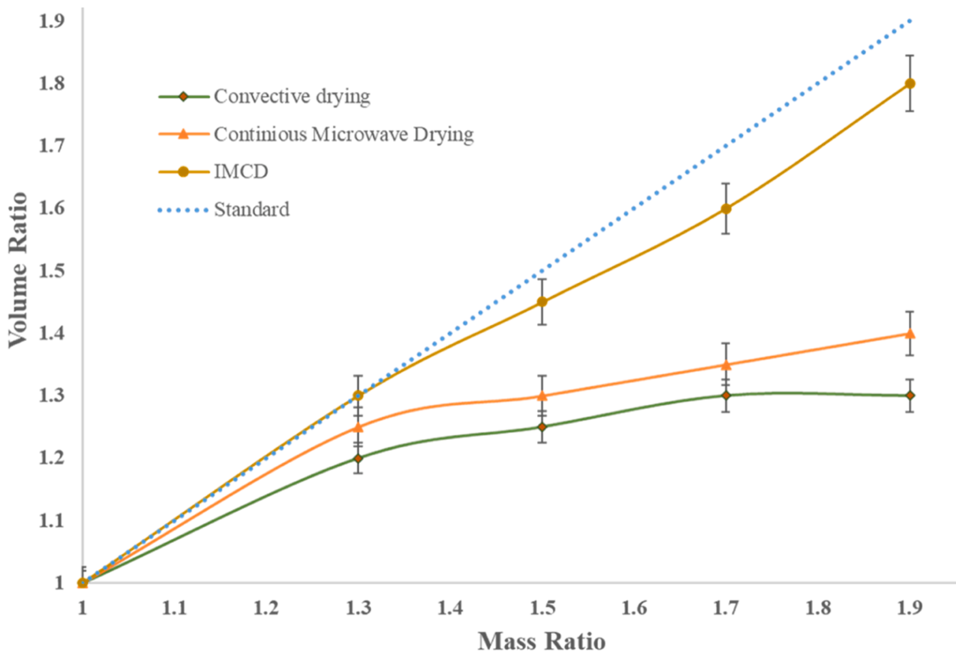


Fig. 8. Correlation between volume ratio and mass ratio of the sample of different drying conditions.

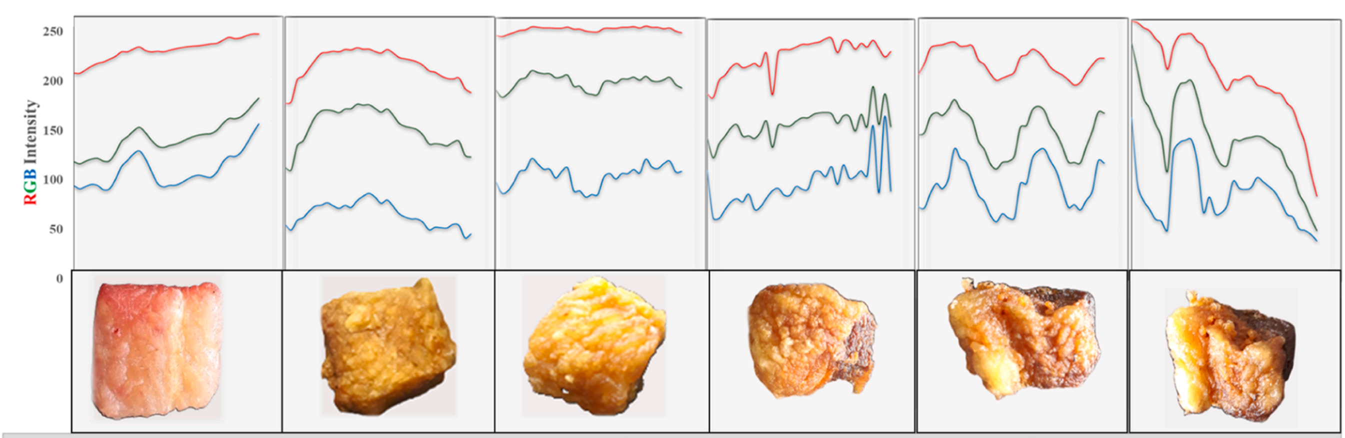
pieces thatn that of in hybrid drying. Continuous microwave drying often leads to thermal runaway and cellular collapse due to rapid internal vapor pressure buildup. In contrast, IMCD moderates this effect by allowing pressure equalization during the OFF periods, which helps preserve the microstructure of the fish tissue. This preservation is indirectly supported by the observed improvements in rehydration capacity and reduced shrinkage, which are commonly associated with better structural integrity (Joardder and Karim, 2023; Joardder et al., 2015; Pham et al., 2017; Joardder et al., 2015; Joardder et al., 2017).

3.6. Appearance

Fig. 9 show the colour changes (ΔE) and how evenly the colour is spread in pangas fish samples dried using different methods. ΔE represents the total colour difference between the fresh and dried samples.

The color uniformity of dried fish samples is a critical quality parameter, influenced by the drying method and conditions. The Fresh sample serves as a baseline, showing high uniformity and minimal color variation. Among the dried samples, IMCD PR 4 and PR 5 stands out with high uniformity, suggesting an effective drying process that preserves color consistency. In contrast, IMCD PR 3 and CMW exhibit significant color variation, indicating potential issues with the drying process and this are the consequence of the uneven heat distribution due to hot spot formation during continuous or more frequent application of MW.

As illustrated in Fig. 9, IMCD exhibits comparatively lower ΔE values than both CD and MCD, indicating its superior effectiveness in



Factor	Fresh	Convective	IMCD PR 5	IMCD PR 4	IMCD PR 3	CMW
Red	231.9 ± 15.5	207.4 ± 15.6	243.6 ± 2.7	214.9 ± 16.8	211.4 ± 13.0	201 ± 41.004
Green	158.9 ± 37.3	146.1 ± 18.7	192.5 ± 6.8	149.0 ± 14.3	142.9 ± 20.8	140 ± 41.449
Blue	125.0 ± 32.0	62.2 ± 11.9	102.3 ± 10.5	88.3 ± 22.5	90.1 ± 21.7	85 ± 29.930
ΔE_{RGB}	-	68.6	42.2	41.7	43.5	57.4

Fig. 9. Colour changes and distribution of sample at different drying conditions.

preserving the colour of fish samples during the drying process. The relatively higher ΔE value observed for IMCD at PR 3, compared to PR 4 and PR 5, suggests the occurrence of initial hotspot phenomena during the IMCD (PR 3) treatment. Similar improvement of product quality has been reported with other MW hybrid drying. For instance, HP-MW drying approach notably improved shrimp quality than the MW one (Le et al., 2024). Convective drying (CD) resulted in the highest ΔE value, indicating significant colour alteration. This could be attributed to the prolonged exposure to heat and air during the convective drying process. Microwave drying (CMW) also led to noticeable colour changes, although to a lesser extent compared to convective drying. This is due to the dark brown color developed due to significant hot stop during continuous application of MW. Similar lower scores of microwave-dried carrots at 200 W in the sensory tests has been reported by G. Yildiz (Yildiz, 2022)

It is difficult to refer single common factors of colour change during different type of drying as colour change specially pronounced brownish color in dried fish samples. This can be resulted from various factors associated with different drying approaches, including temperature and time exposure, oxygen exposure, moisture content and water activity, microwave heating, rate of heat transfer, and surface characteristics. Which eventually results in the Maillard reaction in fish, due to its high protein content, leads to the formation of brown pigments and complex flavors during drying. Moreover, oxidation of fats in fish, rich in unsaturated fats, produces brownish compounds. These factors collectively contribute to the more pronounced browning in dried fish.

Overall, the results highlights the importance of drying method and parameters in preserving the colour quality of dried samples, with IMCD showing potential for minimizing colour changes compared to convective and microwave drying methods.

4. Conclusion

The research introduces a unique hybrid drying system that combines intermittent microwave energy with convective hot air. In the comparative analysis of three fish drying methods-convective drying (CD), continuous microwave convective drying (CMC), and intermittent microwave convective drying (IMCD)-several key findings emerged.

- While CMC exhibited the shortest drying time, the quality of the dried samples was inferior compared to those dried using IMCD. Despite consuming energy at a level comparable to CMC, IMCD demonstrated significantly superior overall quality in comparison to both CMC and CD.
- IMCD stands out as the most promising option for fish drying due to several compelling reasons. Firstly, it achieves remarkable energy efficiency, requiring approximately 25 times less energy compared to convective drying, with an energy requirement of only 1.11 MJ/kg.
- Additionally, the protein content of fish dried using IMCD was notably higher at 22.59 W/W %, indicating better nutrient retention. Furthermore, IMCD products exhibited lower colour change, better appearance, and less shrinkage compared to those dried using hot air methods.
- While the findings are promising, there are opportunities for further development. The use of a modified domestic microwave system served well for experimental purposes but may require adaptation for industrial-scale implementation. Incorporating real-time internal temperature and moisture profiling could further refine process control and optimization. Additionally, expanding the range of food samples tested would help validate the broader applicability of IMCD across different products. These considerations offer valuable directions for future research and technological advancement.
- Moreover, IMCD shows strong potential for industrial fish drying due to its modular design and compatibility with existing systems. It can be scaled up effectively for commercial use. Key areas for optimization include pulse ratio adjustment, energy input control, and real-time moisture sensing, which can improve efficiency and product quality. Economically, IMCD offers benefits like reduced drying time and lower energy costs. Environmentally, it supports sustainability by cutting energy use and carbon emissions. With further development, IMCD could become a cost-effective and eco-friendly solution for large-scale fish drying operations.

Ethical statement - studies in humans and animals

No Ethical Statement is required as this study does not involve studies in humans or animals.

CRediT authorship contribution statement

Mohammad U.H. Joardder: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Conceptualization. **Abdul Mojid Parvej:** Writing – original draft, Visualization, Methodology, Investigation. **Md. Fahim Shahriar:** Writing – original draft, Methodology, Formal analysis. **Md. Fahim Faysal:** Writing – original draft, Investigation. **Md. Mostafizur Rahman:** Methodology, Investigation. **Azharul Karim:** Writing – review & editing, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this manuscript.

Data availability

Data will be made available on request.

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