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PERFORMANCE EVALUATION OF NATURAL AND FORCED CONVECTION IN SOLAR DRYERS FOR MULLET FISH

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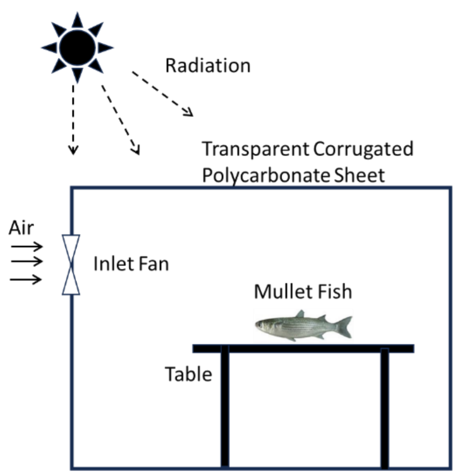
Graphical abstract



Abstract

Ombak Damai Trading, a Malaysian company specialising in dried mullet fish, needed to dry the fish faster to meet growing demand. They reduced the drying time from 1-2 days to 3-4 hours using a solar dryer. The dryer was equipped with an IoT (Internet of things) weighing system for precise monitoring and data collection. Two inlet fans were added for forced convection drying. Measurements of weight, temperature, and humidity were taken for ten days. The forced convection system was found to be 85.78% effective, compared to 59.36% for natural convection. Moisture analysis revealed that the forced convection system removed more moisture, with a maximum percentage of 36% compared to 22% for natural convection. Forced convection also had a higher drying rate of 60.17 g/hour compared to 37.83 g/hour for natural convection. These findings can help seafood businesses optimise the drying process and achieve target moisture levels. Further studies are recommended to examine the forced convection system's commercial scalability, as well as the effects of drying on nutritional content and sensory qualities.

Keywords: Solar Dryer, force convection, natural convection, drying rate, mullet fish, IoT weighing system

Abstrak

Ombak Damai Trading, sebuah syarikat Malaysia yang mengkhusus dalam ikan belanak kering, perlu mengeringkan ikan dengan lebih cepat untuk memenuhi permintaan yang semakin meningkat. Mereka mengurangkan masa pengeringan daripada 1-2 hari kepada 3-4 jam menggunakan pengering suria. Pengering tersebut dilengkapi dengan sistem penimbang IoT (Internet benda) untuk pemantauan dan pengumpulan data yang tepat. Dua kipas salur masuk ditambah untuk pengeringan perolakan paksa. Pengukuran berat, suhu, dan kelembapan diambil selama sepuluh hari. Sistem perolakan paksa didapati 85.78% lebih berkesan, berbanding 59.36% untuk perolakan semula jadi. Analisis kelembapan mendedahkan bahawa sistem perolakan paksa mengeluarkan lebih banyak lembapan, dengan peratusan maksimum 36% berbanding 22% untuk perolakan semula jadi. Perolakan paksa juga mempunyai kadar pengeringan yang lebih tinggi iaitu 60.17 g/jam berbanding 37.83 g/jam untuk perolakan semula jadi. Penemuan ini boleh membantu perniagaan makanan laut mengoptimumkan proses pengeringan dan mencapai tahap kelembapan sasaran. Kajian lanjut disarankan untuk mengkaji skalabiliti komersial sistem perolakan paksa, serta kesan pengeringan pada kandungan nutrisi dan kualiti deria.

Kata kunci: Pengering suria, perolakan paksa, *perolakan semulajadi,* kadar pengeringan, ikan belanak, sistem penimbang IoT

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1.0 INTRODUCTION

Solar drying is a sustainable and cost-effective method for preserving agricultural products and reducing energy consumption. It has gained significant attention worldwide, especially in countries with warm and sunny climates like Malaysia [1]. Malaysia's equatorial location makes it ideal for solar energy utilisation for drying as it receives abundant solar radiation throughout the year [2]. Malaysia has recognised its potential for solar energy and has been increasingly adopting renewable energy, particularly in solar photovoltaic applications in recent years [3].

Significant developments and research initiatives in Malaysia aim to enhance the efficiency and effectiveness of solar drying systems. Studies have focused on the energy analysis of hybrid solar dryers with PV systems and solar collectors for drying agricultural products such as mint [4]. Moreover, there have been investigations into the feasibility of solar-enhanced drying of woody biomass and the development of energy storage chambers to enhance solar drying of grains at night [5, 6, 7]. These efforts reflect the ongoing interest in improving the performance and capabilities of solar drying technologies in Malaysia. Solar drying has also been applied to sewage sludge, coal slime, and tomato pomace waste, demonstrating the versatility of solar drying systems to address diverse drying needs [8, 9, 10]. The potential economic and environmental benefits of solar drying have been highlighted, with studies emphasising its cost-effectiveness and role in reducing costs for small and medium producers [10]. Furthermore, solar drying has been highlighted as a non-polluting and economical drying process, especially when it comes to enhancing the shelf life of food materials [11].

Significant progress has recently been made in solar drying technologies, particularly in natural and forced convection systems. Research studies and technological innovations have driven this progress to improve solar drying processes' efficiency, performance, and sustainability. Studies on natural convection solar dryers have focused on analysing heat transfer coefficients, thermal effusivity, mathematical models of drying kinetics, and economic assessments of low-cost solar drying systems [12]. In addition, the drying performance and quality assessment of agricultural products, such as cassava, has been conducted, considering parameters such as drying time, moisture content, pH, peak viscosity, starch content, and microbial contamination [13]. Moreover, the importance of external factors, including relative humidity, airflow rate, and drying temperature, has been reviewed to understand their impact on the final quality of dried food products [14].

Forced convection solar dryers have significantly improved drying rates compared to natural convection systems. The higher drying rate in forced convection runs can be attributed to the higher mass transfer coefficient associated with forced convection, resulting from the reduced gas mass transfer resistance due to higher air velocity [15]. It was also reported that implementing forced convection into a natural convection setup could enhance exergy flow and temperature control, showcasing the potential for enhanced performance and energy utilisation in forced convection system [12]. Additionally, forced convection dryers have the capability to operate as natural convection dryers, providing versatility in drying operations [16]. Several designs of forced convection solar dryers have been proposed for drying applications, indicating ongoing advancements in this direction [17]. Direct solar irradiance to support the drying process through photovoltaics for forced air circulation further exemplifies the technological advancements in forced convection systems [18]. Additionally, forced convection grain dryers have been found to be more efficient and achieve greater drying rates than natural convection dryers, highlighting the superiority of forced convection technology in drying applications [19].

In contrast, natural convection solar dryers have been associated with limitations such as drying exposure, susceptibility to pests and rodents, and over-dependence on sunlight, which can be addressed by forced convection systems [20]. Furthermore, the collection efficiency and drying efficiency of natural convection solar dryers have been lower than forced convection systems, indicating the superior performance of forced convection technology in achieving efficient drying [21]. In summary, forced convection solar dryers have demonstrated superior drying rates and efficiency compared to natural convection systems, showcasing the potential of forced convection technology to improvise and enhance the drying process.

Ombak Damai Trading is a local company from Malaysia that specialises in producing dried fish from Mullet fish. The raw fish is obtained from nearby fishermen and fishmongers in Tanjung Piandang, Kuala Kurau. Previously, the company dried the fish in an open environment, which took days to dry the fish depending on the weather. This led to an inconsistent drying process because the output heavily depended on the weather. For inexperienced workers, predicting how long the drying process would take too much effort. Worse, the fish could not be dried during rainy days. The company introduced a solar dryer in a closed greenhouse to improve the drying process and allowed them to dry the fish regardless of the weather. As the previous natural convection setup did perform acceptable drying performance, the new setup has added an inlet fan that improves the drying performance compared to natural convection. With this setup, about 200kg of fish can be processed within 2-3 hours to produce dried fish. The new setup has made drying more consistent, predictable, and efficient.

2.0 METHODOLOGY

2.1 Solar Dryer Setup

Figure 1 shows the schematic floor of the solar dryer with a 7.6 m wide and 11.2 m length. The height of the solar dryer is 1.8 m at the side and 2.4 m at the centre of A type roof. The solar dryer is separated into two sections: drying and preparation areas. Transparent corrugated polycarbonate sheets are used for the wall and the roof of the drying section. The specification of the sheets can be referred to in Table 1. The brick wall was used for the preparation area, while the roof was constructed using corrugated sheet panels. The floor dimensions of the drying area are 6 m x 7.6 m. Figure 2 shows the drying area section with a concrete floor. Two 16-inch inlet fans were placed at the centre-top of the drying area, as shown in Figure 3. The fan specifications are shown in Table 2. The preparation area was intended to prepare the fish prior to the drying process, which can prevent workers from the heat from the sun while laying down the fish on the tray. There is a door between the drying area and the preparation area to allow workers to enter the drying area after the preparation. Relative humidity and temperature sensors were placed at the inlet and inside the solar dryer. The specifications of the sensor are shown in Table 3.

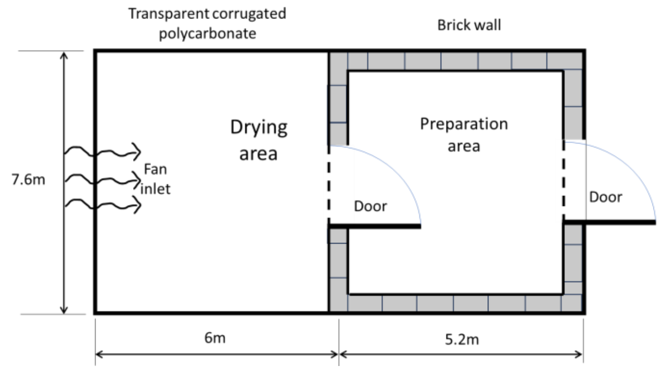

Figure 1 Schematic floor dimension of solar dryer

Table 1 Specification of polycarbonate sheet

Specifications	Values
Thickness	2 mm
Thermal conductivity	0.22 W/mK
Thermal resistance	0.17 m^2K/W

Figure 2 Drying area

Figure 3 Inlet fan

Table 2 Specification of inlet fan

Specifications	Values
Voltage	240 V
Diameter	400 mm
Max motor speed	1350 RPM
Velocity	0.8 m/s

Table 3 Specification of relative humidity and temperature data logger

Specifications	Values
Model	Benetech GM1365
Temperature range	-30 - 80 ℃
Relative humidity range	0 – 100 %RH
Weight	49 g

2.2 IoT Weighing System for Data Logging and Monitoring

An IoT (Internet of Things) weighing system was designed to facilitate the data-logging process during the experimental work. The working mechanism of the system can be summarised in Figure 4. The system is controlled by an Arduino MKR 1010 board as the controller and powered by SAM21 Cortex-M0+ ARM MCU, which has a frequency between 32.768kHz (RTC) and 48MHz. It also supports WiFi connectivity up to 150 Mbps and can accommodate an array of 34 programmable GPIOs. Up to 8 channels of 10-bit ADC and 2 channels of 8-bit DAC can be used for the board.

The FC2231 Compression Load Cell was used as a sensors for compression load input. With a measuring range spanning 0 to 4.6 kilograms per unit (equivalent to 18.4 kilograms), it capably fulfils its purpose. Display functionalities are realised through a 4*20 i2C LCD, while the TFT display harnesses a graphics-based approach, transcending the limitations of a conventional LCD. Power requisites for this undertaking encompass AC 240 V, DC 12 V, and DC 3.3 V. The summary of the main components used for the system is shown in Table 4.

The Arduino MKR 1010 collects sensor data, presents it on the device's LCD Display, and transmits it to the server. With WIFI capabilities, it operates as a WIFI client, facilitating a direct connection to the WIFI Router. Employing the Arduino IoT Cloud application, which serves as the IoT platform, the captured sensor data journeys to the Arduino IoT Cloud Server. The data can then be visualised through the IoT Remote App, which is compatible with Android and iOS devices. Figure 5 provides visual insights into the sequential flow of data from the Arduino MKR 1010 to the Arduino IoT Cloud server and subsequently to the IoT Remote App.

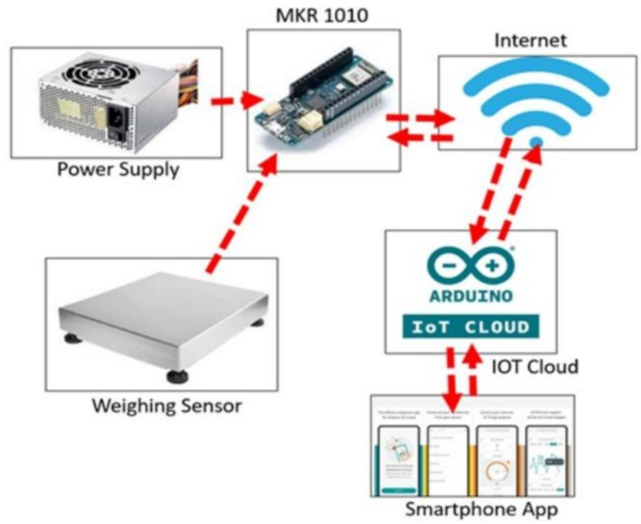

Figure 4 IoT weighing working mechanism

Table 4 Main Components of IoT Weighing System

Specifications	Values
Main controller board and WiFi	Arduino MKR 1010
Weighing sensor	FC2231 Compression Load Cell
Display	2*20 12C LCD

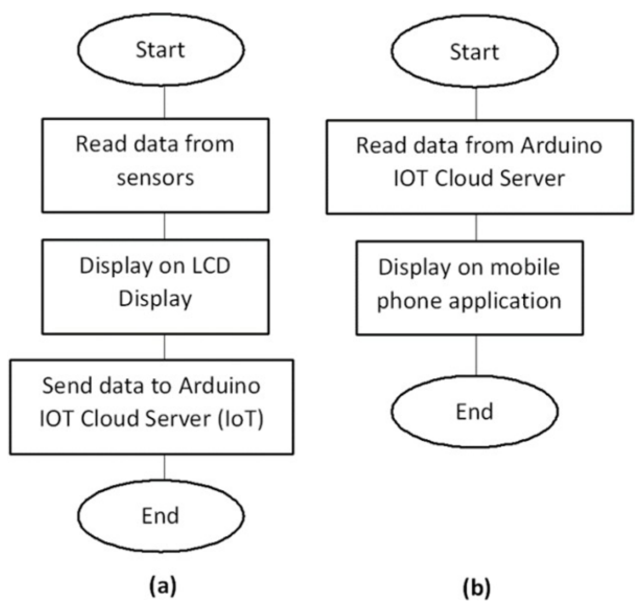

Figure 5 Algorithm data transfer (a) by Arduino MKR 1010 to Arduino IoT Cloud Server and (b) from Arduino IoT Cloud server to IoT Remote App

2.3 Experimental Procedure

A series of experiments was conducted on the process of drying mullet fish using a solar dryer. The fish were cleaned, gutted, and soaked in salt water for two nights before being dried. The experiment was carried out over six days, with 250g of fish being placed in the dryer on the first day, while another 250g of fish was open sun-dried for comparison purposes. On days two to six, fish of varying weights (120kg, 90kg, 60kg, 30kg, and 1kg) were placed in the dryer, and only 1kg of fish was weighed for measuring purposes. The weight changes of the fish were recorded by a weighing system connected to the cloud storage, while temperature and humidity changes were monitored using data loggers (GM1365) placed both inside and outside the dryer. The weight, inside temperature, relative humidity, outside temperature, and relative humidity were recorded at the interval of 30 minutes, from 9 am to 3 pm. For each varying weight (120kg, 90kg, 60kg, 30kg, and 1kg), the experiments were done on different days. The same procedure was repeated with both inlet fans being turned on (each fan ran at a fixed speed of 0.8m/s) for forced convection drying. Both inlet fans were turned down for natural convection drying experiments.

2.4 Performance Evaluation of Drying

The instantaneous moisture removal rate (MRR_t) of mullet fish can be determined by dividing the change in overall weight of mullet fish between two consecutive measurements by the time interval of the measurements [22], as shown in equation (1). The average moisture removal rate of mullet fish can be determined by equation (2) was calculated using the following equations:

$$MRR_t = \frac{Final\ Weight - \text{Initial}\ Weight}{Drying\ Duration\ (0.5 hour)} \quad (1)$$

$$Average\ MRR = \frac{MRR_t}{Total\ drying\ time\ (6\ hours)} \quad (2)$$

The heat transfer through the natural and forced convection can be obtained by equations (3), (4), and (5) [23, 24].

$$Q_{conv} = U \cdot A \cdot \Delta T \quad (3)$$

$$U = \frac{1}{R_T} \quad (4)$$

$$R_T = R_o + \frac{L}{k} + R_i \quad (5)$$

here,

Q_{conv} = Heat transfer through convection (W)
U = Thermal transmittance coefficient (W/m^2℃)
A = Contact area of the roof (m^2)
ΔT = Temperature difference (℃)
R_T = Total thermal resistance (m^2)
R_o = External air film resistance (m^2 K/W)
R_i = Internal air film resistance (m^2 K/W)
k = Thermal conductivity of heat absorber (W/m℃)
L = Thickness of heat absorber (m)

Solar dryer efficiency, η_D can be obtained in equation (6) [25, 26, 27].

$$\eta_D = \frac{m_w \times \Delta \text{Hl}}{A \times I \times t_{ex}} \quad (6)$$

Where,

m_w = Moisture evaporated (kg)
ΔHl = Latent heat of vaporisation of water (2257 kJ/kg) [28]
A = Area of solar dryer (m^2)
I = Average Solar intensity (W/m^2)
t_{ex} = Total drying time (s)

The area of the solar dryer was based on the solar dryer roof area, which was 9.015m^2. Average solar intensity, I was estimated in equation (7).

$$I = \frac{I_{est}}{D_h} \quad (7)$$

Where,

I_{est} = Estimated daily solar intensity (Wh/m^2)
D_h = Daylight hours in a day (h)

The estimated daily solar intensity for Perak, Malaysia, is approximately $5kWh/m^2$ [29] and daylight hours in a day in Malaysia is approximately 12 hours [30].

3.0 RESULTS AND DISCUSSION

3.1 Drying Behaviour on Natural Convection and Forced Convection

The weight changes of Mullet fish, indoor and outdoor temperature, indoor and outdoor relative humidity and moisture removal rate of mullet fish for different weights in natural convective drying are shown in Figure 6, Figure 7, Figure 8, Figure 9 and Figure 10. Regardless of the different weights of mullet fish that were being dried inside the solar dryer, the temperature inside the dryer was higher than the outside temperature. Higher temperatures inside the dryer can expedite the drying process [31] as compared to the outside temperature. Contrary to the outside environment, the relative humidity inside the solar dryer was lower for all weights of mullet fish. This indicates that the drying process inside the solar dryer would be significantly more effective than drying the fish under normal outside conditions. The reduction of relative humidity can expedite the drying process, as it results in a greater driving force for moisture removal by increasing the moisture absorption capacity of air, thereby augmenting the rate of drying [32].

On the overall trends of weight changes of mullet fish, temperature for both inside and outside solar dryer and relative humidity inside and outside the dryer shows a similar pattern regardless of the different weights of mullet fish placed inside the dryer. The temperature of both inside and outside the dryer increased from the start of 9 am until the end of 3 pm while relative humidity for both inside and outside the dryer declined in the opposite direction.

Moisture removal rate, however, fluctuated throughout the drying period for all different weights. The average moisture removal rates (from 1kg of the sample) for 120 kg, 90 kg, 60 kg, 30kg and 1 kg were 28.83 g/hr, 35.67 g/hr, 37.67 g/hr, 36.17 g/hr, and 37.83 g/hr, respectively. It was found that there was no significant difference in the average removal rate for the different weights of mullet fish except for 120kg of mullet fish, where the average drop to 28.83 g/hr. This may be due to limited air movement to remove the moisture from the dryer under natural convection since the amount of moisture increases as the amount of mullet fish increases in the dryer.

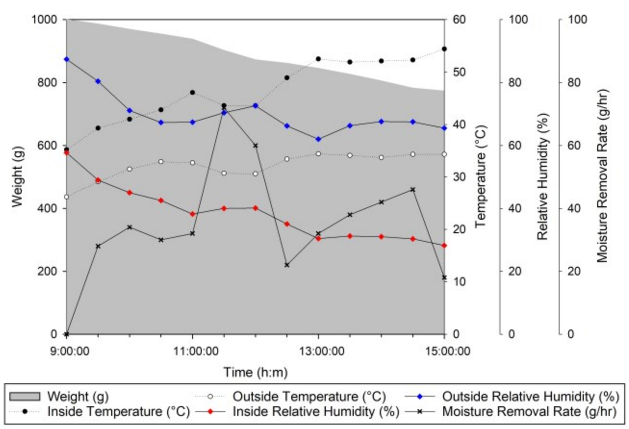

Figure 6 Natural convection drying (1kg)

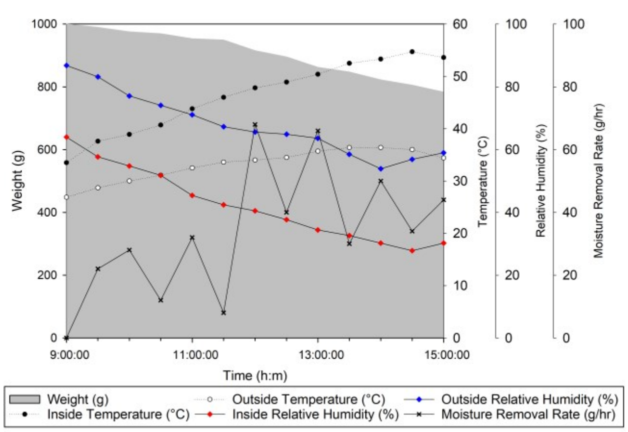

Figure 7 Natural convection drying (30kg)

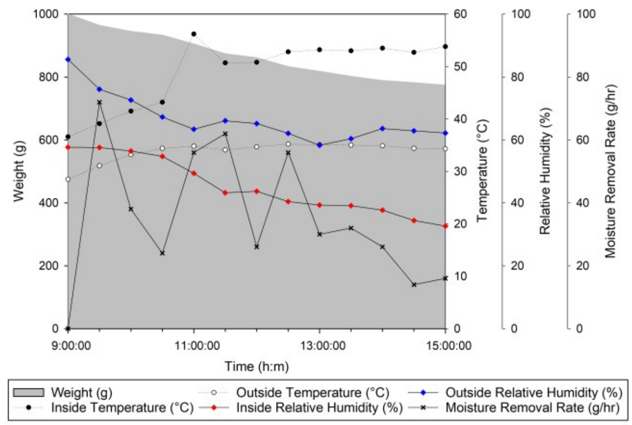

Figure 8 Natural convection drying (60kg)

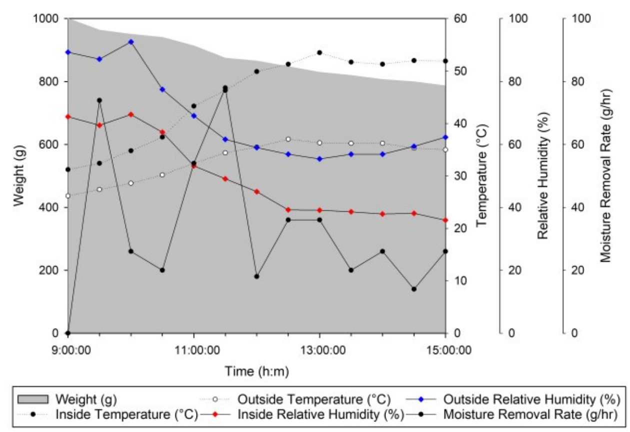

Figure 9 Natural convection drying (90kg)

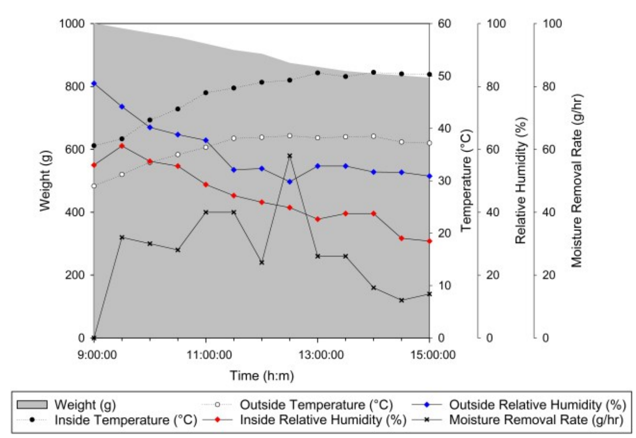

Figure 10 Natural convection drying (120kg)

Figure 11, Figure 12, Figure 13, Figure 14, and Figure 15 display the weight fluctuations of Mullet fish, as well as the corresponding inside and outside temperature, inside and outside relative humidity, and moisture removal rate. These observations were made during forced convective drying and were recorded for different weights of Mullet fish. Temperature, relative humidity, and moisture removal rates for forced convection drying exhibited almost similar patterns to natural convection drying, where the inside temperature was higher than the outside temperature while the inside relative humidity was lower than the outside relative humidity. In general, the temperature inside the solar dryer increased significantly from the beginning of the experiment until 12 pm, when it started to incline slowly for different weights of mullet fish being dried. The temperature, however, started to decline slowly after 12 pm while relative humidity gradually increased when drying 1 kg of mullet fish for both inside and outside solar dryer, as shown in Figure 11. This may be explained by the cloudy weather in the evening.

Despite variations in the weight of the Mullet fish being dried, the rate of moisture removal fluctuated without a specific pattern throughout the drying period. The average moisture removal rates (from 1kg of the sample) for 120 kg, 90 kg, 60 kg, 30kg and 1 kg were 42.17 g/hr, 44.00 g/hr, 50.33 g/hr, 53.50 g/hr, and 60.17 g/hr, respectively. These results suggest that the average moisture removal rates decreased as the total weight of Mullet fish in the dryer increased from 1 kg to 120 kg. The most significant observation was that the average moisture removal rate for forced convection drying was superior to natural convection drying for the respective total amount of Mullet fish dried. Previous studies have consistently shown that forced convection results in a significantly higher drying rate compared to natural convection [15], [19].

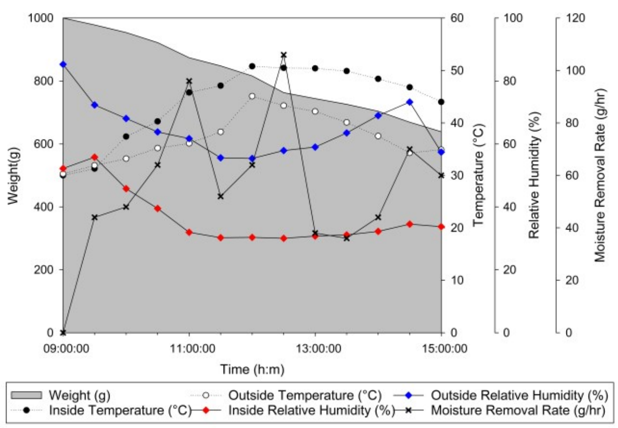

Figure 11 Forced convection drying (1kg)

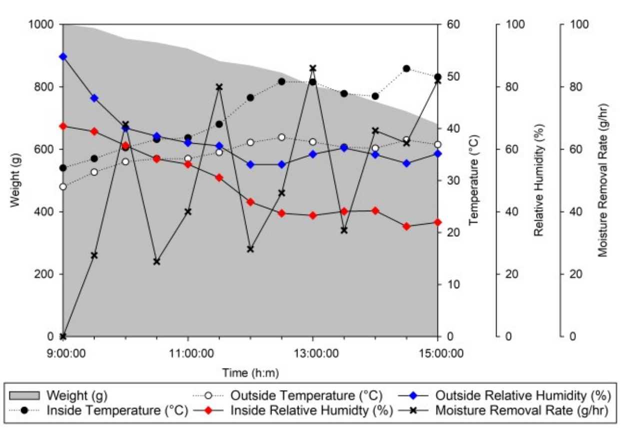

Figure 12 Forced convection drying (30kg)

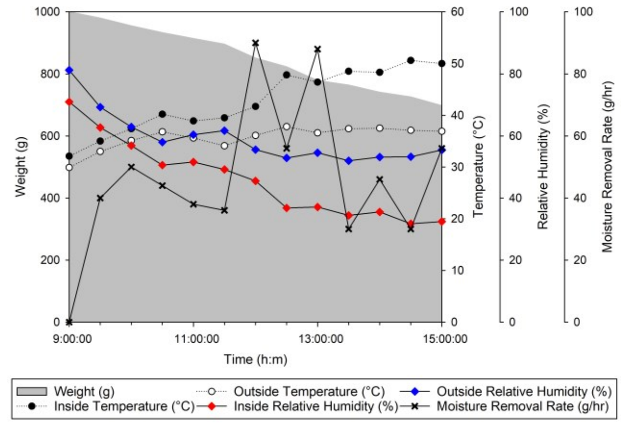

Figure 13 Forced convection drying (60kg)

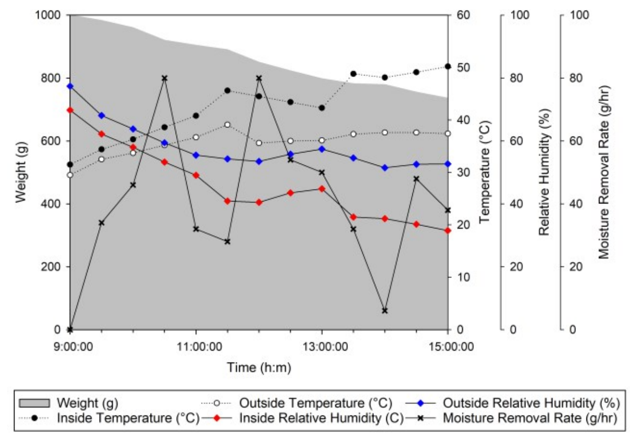

Figure 14 Forced convection drying (90kg)

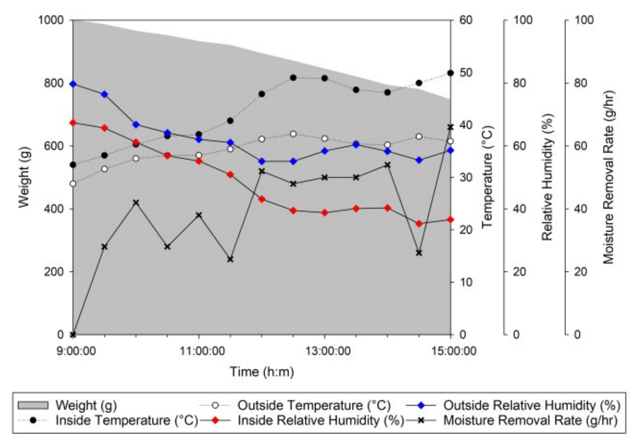

Figure 15 Forced convection drying (120kg)

3.2 Moisture Loss

Total moisture loss for different weights under forced and natural convection drying is illustrated in Figure 16. In general, forced convection drying shows higher total moisture loss compared to natural convection drying for the equivalent total weight of Mullet fish being dried within 6 hours. Total moisture loss for forced convection drying decreased from 36% to 25% as the total weight of Mullet fish increased from 1 kg to 120 kg. In natural convection drying, no significant change in total moisture loss was recorded between 21% and 22%, even though the total weight of Mullet fish being dried was varied. However, there was a significant change in total moisture loss at 17% when 120 kg of Mullet fish was dried. This may be due to limited air movement under natural convection, as described by previous researchers [33].

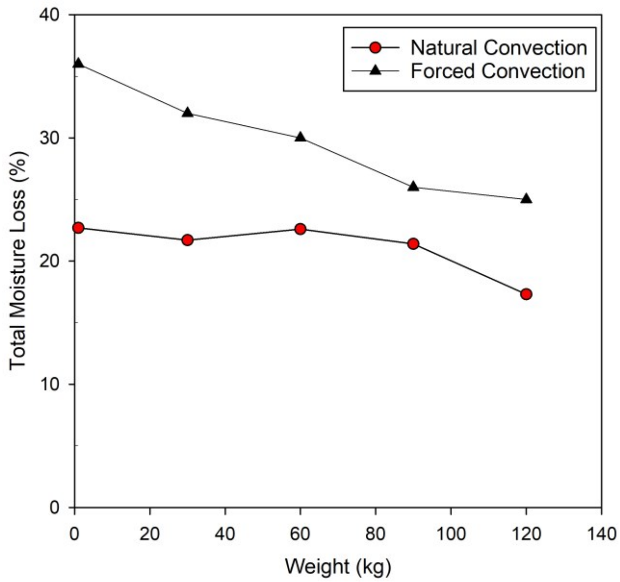

Figure 16 Total moisture loss

3.3 Dryer Efficiency

Figure 17 summarised the dryer efficiency in natural convection drying and forced convection drying under varied total mullet fish being dried. In forced convection drying, the dryer efficiency increased from 0.65% up to 59.36% when the total weight being dried increased from 1 kg to 120 kg. There was a slight increase in the dryer efficiency from 55.07% to 59.36% when the total weight increased from 90 kg to 120 kg. For forced convection drying, the dryer efficiency increased significantly from 1.03% to 85.78% when the total weight increased from 1 kg to 120 kg. The result demonstrates a significant efficiency increase in comparison to natural convection drying. These findings may be explained by low buoyancy-induced airflow inside natural convection dryers, which limits their drying capacity and efficiency [34].

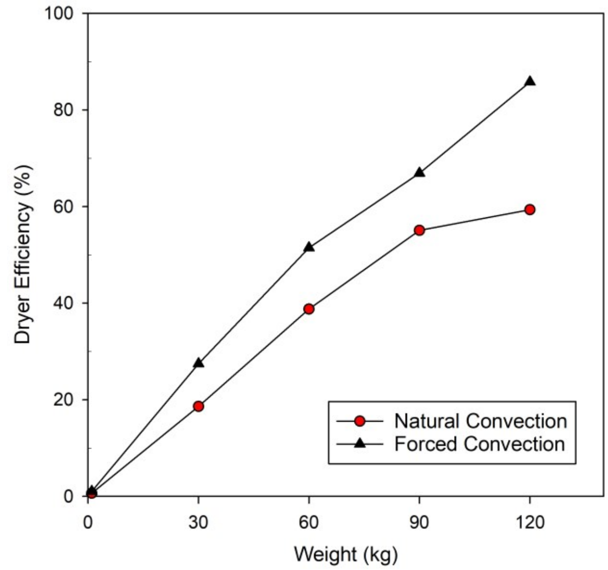

Figure 17 Dryer efficiency

4.0 CONCLUSION

This study aimed to determine which drying method is more effective for mullet fish: forced or natural convection. The results showed that forced convection is significantly better than natural convection, with a drying rate of 42.17 g/hr to 60.17 g/hr compared to natural convection's 28.17 g/hr and 37.83 g/hr. These findings have contributed to a significant total moisture loss in forced convection drying at 25% to 36% compared to 21% to 22% of total moisture loss in natural convection. In terms of dryer efficiency, forced convection obtained significantly higher efficiency, up to 85.78%, in comparison with natural convection, which could only achieve 59.36%. These findings indicate that forced convection is a more efficient method for drying mullet fish.

It is important to note that seasonal variations can significantly affect the parameters studied, such as temperature, humidity, and drying rate. Seasonal changes could result in different trends and efficiencies in the drying process, potentially altering the performance of both natural and forced convection methods. However, this study was conducted over several days within a single season, which limits the generalizability of the findings. Further studies are required to investigate the impact of seasonal variations on the drying performance of solar dryers. Such studies would provide a more comprehensive understanding of the drying process under different climatic conditions and could help optimize the drying system for year-round operation.

To sum up, this research clearly establishes forced convection as superior to natural convection in terms of drying rate, total moisture loss, and drying efficiency for mullet fish. Future research should focus on addressing the limitations related to seasonal variations to enhance the robustness and applicability of the findings across different environmental conditions.

Acknowledgement

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Conflicts of Interest

The author(s) declare(s) that there is no conflict of interest regarding the publication of this paper.

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