

# Lean Six Sigma–Based Optimization of *Wolffia Globosa* Drying Technologies

**Phornpilat Senanok**

System Engineering Program, School of Industrial Engineering  
Institute of Engineering Suranaree University of Technology  
Nakhon Ratchasima, Thailand  
[phornpilat.26@gmail.com](mailto:phornpilat.26@gmail.com)

**Nara Samattapapong**

School of Industrial Engineering, Institute of Engineering  
Suranaree University of Technology Nakhon Ratchasima  
Thailand  
[nara@sut.ac.th](mailto:nara@sut.ac.th)

## Abstract

The industrial utilization of *Wolffia globosa* as a sustainable plant-based protein source is limited by its extremely high moisture content (~96% on a wet basis), which create challenges in mass transfer efficiency, process stability, and shelf-life management. This study applied the Lean Six Sigma DMAIC framework to evaluate and optimize dehydration technologies for *Wolffia globosa*. Three drying methods—hot air drying (HAD), microwave vacuum drying (MVD), and freeze drying (FD)—were investigated based on drying kinetics, heat and mass transfer mechanisms, and critical-to-quality (CTQ) attributes, including water activity ( $a_w$ ) and total color difference ( $\Delta E$ ). Experiments were conducted under controlled conditions with replication to ensure statistical reliability. Freeze drying produced the highest physicochemical quality, achieving the lowest water activity ( $a_w < 0.25$ ) and excellent color retention ( $\Delta E \approx 0$ ), but required the longest processing time (720 min) and high energy consumption. Hot air drying exhibited moderate performance, accompanied by greater thermal degradation. Microwave vacuum drying significantly enhanced moisture removal, reducing drying time to 40 min while maintaining acceptable product quality ( $\Delta E = 8.71 \pm 0.12$ ;  $a_w = 0.28 \pm 0.03$ ). Process capability analysis identified MVD as the most suitable technology for scalable *Wolffia globosa* powder production.

## Keywords

*Wolffia globosa*, Microwave vacuum drying, Lean Six Sigma, Drying kinetics, Water activity.

## 1. Introduction

The global food system is currently navigating a period of unprecedented pressure, driven by a burgeoning population, diminishing arable land, and the urgent necessity to transition toward sustainable, low-impact protein sources. Within this context, *Wolffia globosa*, a rootless aquatic plant in the Lemnaceae family commonly known as watermeal, has emerged as a focal point for nutritional research and industrial food technology. Often cited as the smallest flowering plant on Earth, *Wolffia globosa* exhibits a growth rate that is significantly higher than most terrestrial crops, with a doubling time of approximately 24–48 h under optimal conditions. Beyond its rapid biomass accumulation, its nutritional profile is exceptional, containing 20–40% protein (dry weight basis), a complete essential amino acid profile, dietary fiber, and an array of bioactive compounds including phenolics and pigments such as chlorophyll and carotenoids. Despite this immense potential as a sustainable "superfood" or functional

ingredient, the commercial exploitation of *Wolffia globosa* is severely constrained by its physiological characteristics in the post-harvest phase.

This high moisture content creates fundamental technical and economic challenges that prevent *Wolffia globosa* from achieving large-scale commercial success. The primary obstacle is its hyper-hydrated state (96% moisture), which essentially means that for every 100 kg of fresh biomass, only 4 kg consists of actual nutrient solids. This extreme water content acts as a catalyst for rapid microbial proliferation, making the plant highly perishable and difficult to manage within a standard supply chain. From a logistical standpoint, transporting fresh *Wolffia* is cost-prohibitive, as over 96% of bulk mass consists of water, significantly increasing logistical costs. Furthermore, for *Wolffia* to be utilized as a functional food ingredient, it must undergo downstream processing, such as milling into a fine powder, to ensure uniform integration into food matrices like bread or meat analogues. Consequently, Dehydration is therefore identified as the pivotal unit operation, bridging the transition from a raw aquatic plant to a scalable industrial raw material depends entirely on developing drying protocols that effectively bridge the gap between processing efficiency and nutritional retention.

While dehydration is a fundamental preservation strategy for reducing water activity and extending shelf life, the selection of an optimal technology necessitates a complex trade-off between physicochemical quality, processing efficiency, and economic viability. Conventional hot air drying (HAD) is widely utilized for its operational simplicity and low capital investment, yet its reliance on convective heat transfer frequently leads to the thermal degradation of bioactive compounds and undesirable chromatic shifts. In contrast, freeze drying (FD) remains the gold standard for quality retention due to its low-temperature sublimation mechanism, which preserves cellular integrity; however, its industrial scalability is severely hindered by protracted processing cycles and prohibitive energy consumption. Emerging as a synergistic solution, microwave vacuum drying (MVD) integrates the rapid moisture diffusivity of volumetric heating with the low-temperature evaporation facilitated by reduced atmospheric pressure. By accelerating drying kinetics while maintaining product quality comparable to lyophilization, MVD offers a promising balance between nutritional retention and the throughput demands of industrial food processing.

Determining the optimal dehydration strategy for *Wolffia globosa* necessitates a multi-faceted and data-driven optimization framework that transcends traditional empirical approaches by systematically balancing product quality, operational efficiency, and industrial feasibility. This research implements the Lean Six Sigma (LSS) DMAIC methodology—structured through the phases of Define, Measure, Analyze, Improve, and Control—to effectively bridge the gap between Lean's focus on waste elimination and Six Sigma's commitment to statistical precision and process stabilization. While the LSS paradigm has historically demonstrated transformative success in traditional manufacturing sectors, its application to the complex processing of emerging plant-based proteins, such as *Wolffia globosa*, remains considerably underdeveloped. Consequently, this study utilizes the DMAIC framework as a rigorous diagnostic tool to evaluate and optimize three distinct drying technologies: hot air drying (HAD), microwave vacuum drying (MVD), and freeze drying (FD). This evaluation integrates fundamental drying kinetics and performance metrics with critical-to-quality (CTQ) attributes, specifically targeting the reduction of water activity ( $a_w$ ) and the minimization of total color change ( $\Delta E$ ). By synthesizing these variables through a systematic lens, the research does not merely seek a superior drying method but aims to identify a robust, scalable engineering protocol. Such a protocol is essential for harmonizing high-fidelity nutritional and organoleptic retention with the demanding throughput and energy-efficiency requirements of modern industrial food processing, ultimately establishing a sustainable pathway for the commercialization of high-stability *Wolffia globosa* ingredients.

## **1.1 Objectives**

This research aims to identify the optimal dehydration technology for *Wolffia globosa* through a comprehensive comparative evaluation of hot air drying (HAD), microwave vacuum drying (MVD), and freeze drying (FD). By integrating an analysis of drying kinetics with the assessment of critical-to-quality attributes—specifically water activity ( $a_w$ ) and colorimetric stability ( $\Delta E$ )—the study provides a granular understanding of moisture transfer mechanisms and post-process product stability. Furthermore, the application of the Lean Six Sigma DMAIC framework facilitates a systematic optimization of the drying unit operations, effectively reconciling technical drying performance with industrial scalability requirements. Ultimately, this study establishes a robust, data-driven protocol for selecting the most efficient drying method to produce high-quality, shelf-stable *Wolffia* powder suitable for large-scale commercial applications.

## **2. Literature review**

Drying is one of the most widely used preservation techniques for high-moisture biological materials and agricultural products. The primary objective of drying is to reduce water activity and inhibit microbial growth, thereby extending the shelf life of food products while maintaining product quality attributes such as color, texture, and nutritional value. Drying processes significantly influence the physicochemical properties of food materials due to simultaneous heat and mass transfer phenomena (Mujumdar, 2014) the physicochemical properties of food materials due to simultaneous heat and mass transfer phenomena during moisture removal. Similarly, Fellows (2017) explained that dehydration plays a critical role in improving the stability and storage capability of food products with high moisture content.

Hot air drying (HAD) is one of the most commonly used drying technologies in the food industry due to its simple operation, relatively low capital investment, and high industrial scalability. In convective drying systems, heat is transferred from hot air to the product surface, resulting in moisture evaporation and subsequent diffusion of internal moisture toward the surface. Krokida et al. (2003) reported that convective drying may cause structural shrinkage and significant changes in product color due to prolonged exposure to thermal conditions. Similarly, Maskan (2001) found that high drying temperatures can lead to degradation of natural pigments and undesirable quality changes in dried products.

Freeze drying (FD), also known as lyophilization, is widely recognized as one of the most effective drying methods for preserving food quality. This process removes water through sublimation under low temperature and vacuum conditions, which minimizes thermal damage to the product structure. According to Ratti (2001), freeze drying can effectively maintain the original color, nutritional components, and cellular structure of food materials. However, the major disadvantages of freeze drying include long drying time and high energy consumption, which limit its economic feasibility for large-scale industrial applications.

Microwave vacuum drying (MVD) has emerged as an advanced drying technology that combines microwave heating with reduced pressure conditions. Microwave energy generates volumetric heating inside the material, which accelerates internal heat transfer and enhances moisture migration. Zhang et al. (2006) reported that microwave-based drying technologies significantly reduce drying time compared with conventional drying methods. Similarly, Feng et al. (2012) demonstrated that microwave vacuum drying can maintain product quality while improving drying efficiency due to rapid moisture evaporation under vacuum conditions.

Recent studies have also emphasized the importance of process optimization in modern food processing industries. Lean Six Sigma (LSS) has been widely adopted as an effective methodology for improving industrial processes by integrating waste reduction principles from lean manufacturing with statistical quality control tools from Six Sigma. George (2005) explained that the DMAIC framework—Define, Measure, Analyze, Improve, and Control—provides a systematic approach for analyzing process variability and improve operational efficiency. Furthermore, Montgomery (2019) highlighted that statistical analysis and process capability evaluation are essential tools for identifying optimal process conditions in industrial systems.

Although numerous studies have investigated various drying technologies for agricultural products, limited research has focused on drying process optimization for *Wolffia globosa*, an emerging sustainable protein source with exceptionally high moisture content. Due to its extremely high moisture content and sensitivity to thermal degradation, the selection of an appropriate drying technology is essential for maintaining product quality while ensuring industrial feasibility. Therefore, this study integrates drying technology evaluation with the Lean Six Sigma DMAIC framework to systematically analyze and optimize the dehydration process of *Wolffia globosa*.

## **3. Methodology**

### **3.1 Lean Six Sigma Framework**

This study applied the Lean Six Sigma (LSS) methodology to systematically evaluate and optimize the drying process of *Wolffia globosa*. The DMAIC framework—Define, Measure, Analyze, Improve, and Control—was adopted as the primary process improvement model (Figure 1). This structured approach enables the identification of process inefficiencies and supports data-driven decision-making for selecting the most appropriate drying technology.

In the Define phase, the main problem addressed in this study was the extremely high moisture content of fresh *Wolffia globosa*, which significantly reduces shelf life and limits its industrial utilization. Therefore, the primary objective of the process improvement initiative was to identify an efficient drying method capable of reducing moisture content while maintaining product quality.

In the Measure phase, key performance indicators (KPIs) were established to evaluate the drying performance and product quality. These indicators included water activity ( $a_w$ ), color change ( $\Delta E$ ), drying time, and effective moisture diffusivity. Water activity was selected as a critical parameter associated with microbial stability and shelf life of dried products. Color change was used as an indicator of thermal degradation during drying. Drying time reflects process efficiency, while effective moisture diffusivity represents the internal mass transfer behavior of moisture within the material.

In the Analyze phase, the drying performance of the three drying methods—hot air drying (HAD), microwave vacuum drying (MVD), and freeze drying (FD)—was compared. Statistical analysis and process evaluation were conducted to determine the relationship between drying conditions and the resulting product quality attributes.

In the Improve phase, optimal drying conditions were identified by balancing processing efficiency and product quality. The performance of each drying technology was evaluated in order to determine the most suitable drying strategy for *Wolffia globosa* dehydration.

Finally, in the Control phase, process capability analysis was conducted to evaluate the stability and reproducibility of the selected drying process. This step ensures that the optimized process can consistently produce high-quality dried *Wolffia* products under controlled operating conditions.

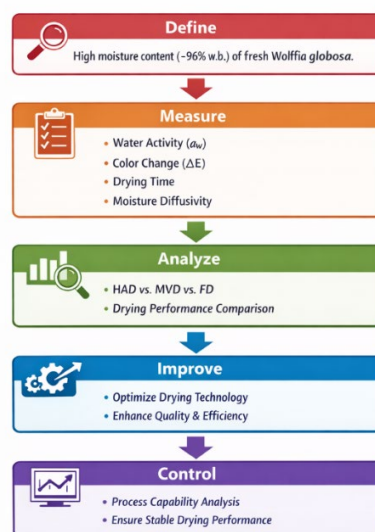


Figure 1. Lean Six Sigma DMAIC framework applied to drying process optimization.

### 3.2 Drying Experiments

Fresh *Wolffia globosa* samples were obtained from [source/supplier] and prepared prior to drying experiments. The initial moisture content of the fresh biomass was approximately 96% (wet basis). Samples were evenly distributed on drying trays at a loading density of [0.20 g/cm<sup>2</sup>] to ensure uniform heat and mass transfer. Three drying technologies were investigated in this study: hot air drying (HAD), microwave vacuum drying (MVD), and freeze drying (FD). These methods were selected because they represent different heat transfer mechanisms and are commonly used in food processing applications. For hot air drying (HAD), the samples were dried in a convective hot air dryer at a temperature of 60°C with an air velocity of 1.5 m/s. Heat transfer occurred primarily through convection between the heated air and the product surface. For microwave vacuum drying (MVD), the samples were placed in a microwave vacuum drying system operating at a microwave power of 360 W and a vacuum

pressure of 0.08 MPa. Microwave energy generated volumetric heating within the samples, while the vacuum environment reduced the boiling point of water and accelerated moisture removal. For freeze drying (FD), the samples were pre-frozen at  $-80^{\circ}\text{C}$  (or specify actual freezing temperature) and then freeze-dried at a shelf temperature of  $-50^{\circ}\text{C}$  under a vacuum pressure of 0.05 MPa. Moisture was removed through sublimation, which preserves the structural integrity of the material. For all drying experiments, the drying process was continued until the samples reached a constant weight, indicating that the equilibrium moisture content had been achieved. Each drying experiment was conducted in triplicate to ensure the reliability and reproducibility of the experimental results.

### 3.3 Quality Analysis

To evaluate the quality of the dried *Wolffia globosa* samples, two critical quality attributes were analyzed: water activity ( $a_w$ ) and color change ( $\Delta E$ ).

#### Water Activity Measurement

Water activity ( $a_w$ ) is a key parameter used to evaluate the microbial stability and shelf life of dried food products. In this study, water activity was measured using a calibrated water activity analyzer. The  $a_w$  value indicates the availability of free water within the product, which directly affects microbial growth and product stability.

#### Color Measurement

Color change was measured using a colorimeter based on the CIELAB color system. The color parameters  $L^*$ ,  $a^*$ , and  $b^*$  were recorded for both fresh and dried samples. The total color difference ( $\Delta E$ ) was calculated to quantify the extent of color change caused by the drying process.

The total color difference was calculated using the following equation:

$$\Delta E = \sqrt{[(L_0 - L)^2 + (a_0 - a)^2 + (b_0 - b)^2]}$$

where

$L_0$ ,  $a_0$ , and  $b_0$  represent the color values of the fresh sample, and

$L$ ,  $a$ , and  $b$  represent the color values of the dried sample.

This parameter provides an objective measurement of color degradation and allows comparison of product quality among different drying methods.

### 3.4 Drying Kinetics Model

Drying kinetics analysis was conducted to understand the moisture transfer behavior during the dehydration process of *Wolffia globosa*. The drying characteristics were evaluated using the moisture ratio (MR), which describes the change in moisture content of the sample over time during the drying process (Table 1).

The moisture ratio was calculated using the following equation:

$$MR = \frac{M_t - M_e}{M_0 - M_e}$$

where

$M_t$  = moisture content at time  $t$

$M_0$  = initial moisture content

$M_e$  = equilibrium moisture content

In many drying studies, the equilibrium moisture content ( $M_e$ ) is relatively small compared with the initial moisture content ( $M_0$ ) and can therefore be neglected. As a result, the moisture ratio can be approximated as:

$$MR = \frac{M_t}{M_0}$$

This parameter was used to analyze the drying behavior of *Wolffia globosa* under different drying technologies.

### Effective Moisture Diffusivity

The internal moisture migration during drying was evaluated by estimating the effective moisture diffusivity ( $D_{eff}$ ). Moisture diffusion within biological materials is commonly described by Fick's second law of diffusion (Fick, 1855).

For slab-shaped materials, Fick's second law can be expressed as:

$$\frac{\partial M}{\partial t} = D_{eff} \frac{\partial^2 M}{\partial x^2}$$

Assuming uniform initial moisture distribution and negligible external resistance, the analytical solution for long drying times can be simplified as:

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

where

$D_{eff}$  = effective moisture diffusivity (m<sup>2</sup>/s)

$L$  = half thickness of the sample (m)

$t$  = drying time (s)

The effective moisture diffusivity ( $D_{eff}$ ) was estimated from the slope of the linear regression of  $\ln(MR)$  vs. drying time ( $t$ ), where slope =  $-\pi^2 D_{eff} / 4L^2$ .

Table 1. Comparison of drying technologies used in this study.

Drying Method	Heat Transfer Mechanism	Drying Time	Product Quality	Energy Consumption	Industrial Feasibility
Hot Air Drying (HAD)	Convective heating	Long	Moderate to low	Low	High
Microwave Vacuum Drying (MVD)	Volumetric microwave heating under vacuum	Short	High	Moderate	High
Freeze Drying (FD)	Sublimation under vacuum	Very long	Very high	Very high	Limited

## 4. Results and Discussion

### 4.1 Drying Performance

The drying performance of the different drying technologies was evaluated based on their heat and mass transfer mechanisms as well as their overall processing characteristics. Three drying methods were investigated in this study: hot air drying (HAD), freeze drying (FD), and microwave vacuum drying (MVD). Convective drying techniques such as hot air drying rely primarily on heat transfer from hot air to the surface of the product. Moisture evaporation occurs gradually from the surface layer while internal moisture diffuses slowly toward the surface. This mechanism generally results in longer drying times and may lead to structural changes in the material. Prolonged exposure to high temperatures may also cause degradation of heat-sensitive compounds such as pigments and bioactive components. In contrast, microwave vacuum drying utilizes volumetric microwave heating to generate internal heat within the sample. Microwave energy interacts directly with water molecules inside the biomass, causing rapid internal evaporation. The application of vacuum conditions reduces the boiling point of water, allowing moisture removal at lower temperatures. Consequently, the drying rate of MVD is significantly higher than that of conventional convective drying methods. Freeze drying operates through a sublimation mechanism in which frozen water is directly converted into vapor under low temperature and vacuum conditions. This mechanism minimizes thermal damage and preserves cellular structure and nutritional compounds. However, the freeze-drying process

requires significantly longer drying time and higher energy consumption compared with other drying technologies. Overall, the comparison of drying mechanisms indicates that microwave vacuum drying provides a significant advantage in terms of drying rate and process efficiency.

#### 4.2 Water Activity Comparison

Water activity ( $a_w$ ) is an important indicator of microbial stability and storage safety for dried food products. Generally, water activity values below 0.60 are sufficient to inhibit microbial growth. The experimental results demonstrated that all drying methods successfully reduced the water activity of *Wolffia globosa* to levels below the microbial growth threshold. Freeze drying achieved the lowest water activity values ( $a_w < 0.25$ ), indicating excellent moisture removal and high product stability. Microwave vacuum drying produced  $a_w$  values of approximately  $0.28 \pm 0.03$ , which are very close to those obtained from freeze drying. This result suggests that MVD can effectively produce shelf-stable dried *Wolffia globosa* products. Hot air drying resulted in slightly higher water activity values due to the slower moisture removal rate associated with convective drying. Nevertheless, the  $a_w$  values obtained from hot air drying were still within acceptable limits for dried food storage. These findings indicate that microwave vacuum drying is capable of achieving microbial stability comparable to freeze drying while maintaining higher process efficiency.

#### 4.3 Color Quality

Color is a critical quality attribute of dried food products because it strongly affects consumer perception and product acceptability. The color characteristics of dried *Wolffia globosa* obtained from different drying methods are summarized in Table 2. Freeze drying showed the best color preservation among all drying methods. The FD samples exhibited the highest lightness value ( $L^* = 44.40 \pm 0.16$ ) and the most negative  $a^*$  value ( $a^* = -8.86 \pm 0.07$ ), indicating the strongest green color, indicating effective preservation of chlorophyll pigments. The relatively high  $b^*$  value ( $16.22 \pm 0.11$ ) further reflects the natural yellow component of the green product of the product. Microwave vacuum drying resulted in moderate color changes compared with freeze drying. The  $L^*$  value decreased to  $38.32 \pm 0.17$ , indicating slightly darker samples, while the  $a^*$  value ( $-4.43 \pm 0.35$ ) showed reduced greenness. The total color difference ( $\Delta E = 8.71 \pm 0.12$ ) indicates noticeable but acceptable color change. Hot air drying yielded  $L^* = 43.79 \pm 0.40$  and the lowest  $\Delta E$  ( $3.01 \pm 0.27$ ), indicating superior color preservation compared to MVD. However, its longer drying time (240 min vs. 40 min for MVD) reduces its industrial competitiveness. Overall, freeze drying produced the best color quality, while microwave vacuum drying maintained acceptable color characteristics with significantly shorter drying time (Figure 2, Figure 3).

Table 2. Experimental Results of Drying Methods for *Wolffia globosa*

Drying Method	$L^*$	$a^*$	$b^*$	$\Delta E$	Water Activity ( $a_w$ )	Drying Time (min)
Freeze Drying (FD)	$44.40 \pm 0.16^d$	$-8.86 \pm 0.07^a$	$16.22 \pm 0.11^d$	$\approx 0$	$< 0.25$	720
Microwave Vacuum Drying (MVD)	$38.32 \pm 0.17^b$	$-4.43 \pm 0.35^c$	$10.01 \pm 0.74^b$	$8.71 \pm 0.12$	$0.28 \pm 0.03$	40
Hot Air Drying (HAD)	$43.79 \pm 0.40^c$	$-6.62 \pm 0.13^b$	$15.03 \pm 0.24^c$	$3.01 \pm 0.27$	$\sim 0.32$	240

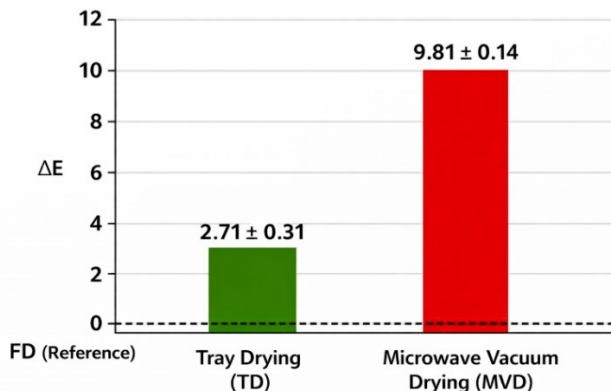


Figure 2. Total Color Difference ( $\Delta E$ ) Comparison

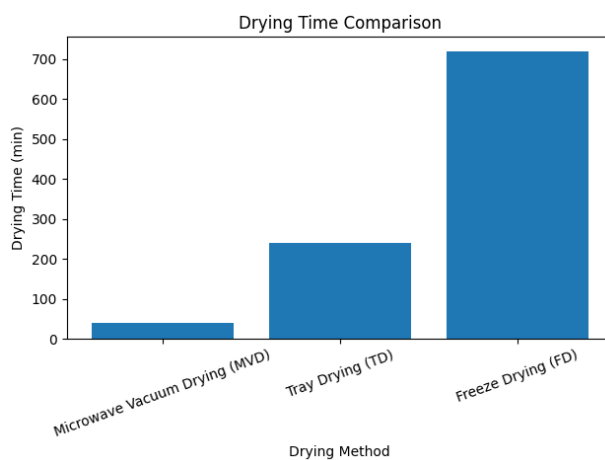


Figure 3. Comparison of drying time for different drying technologies.

#### 4.4 Process Efficiency

Process efficiency is an essential factor in selecting drying technologies for industrial applications. Besides product quality, drying time and energy consumption must also be considered. Freeze drying produced the highest quality product but required extremely high energy consumption, typically 50–100 MJ per kilogram of water removed (cite source). The long drying time and high operational cost limit its applicability for industrial-scale production. Hot air drying requires relatively lower energy input but involves longer processing times, which may reduce production throughput. Microwave vacuum drying demonstrated the most favorable balance between product quality and process efficiency. The combination of volumetric microwave heating and reduced pressure significantly accelerated moisture removal. As a result, MVD reduced drying time by approximately 83% (from 240 min to 40 min) compared with HAD. These advantages make microwave vacuum drying a promising drying technology for large-scale production of *Wolffia globosa* powder (Table 3).

Table 3. Lean Six Sigma Decision Matrix

Criteria	Weight	FD	MVD	HAD
Product Quality	0.35	5	4	3
Drying Time	0.30	1	5	2
Energy Consumption	0.20	1	4	3
Process Stability	0.15	4	5	3
<b>Total Score</b>	1.00	<b>2.75</b>	<b>4.45</b>	<b>2.85</b>

#### **4.5 Lean Six Sigma Process Capability Analysis**

To evaluate process stability and consistency, the drying methods were analyzed using the Lean Six Sigma framework. Process capability analysis was conducted based on the key quality indicators including water activity and color change. The results indicated that microwave vacuum drying demonstrated the most stable and consistent performance among the evaluated drying technologies. MVD produced a coefficient of variation (CV) of [10.71] % for  $a_w$  and [1.38] % for  $\Delta E$ , indicating consistent and reproducible product quality. Although freeze drying produced superior quality in terms of color and water activity, its high energy consumption and long processing time reduce its industrial feasibility. Hot air drying showed greater variability in product quality due to prolonged exposure to thermal conditions. Based on the Lean Six Sigma evaluation, microwave vacuum drying provides the optimal balance between product quality, process efficiency, and process stability. Therefore, MVD can be considered the most suitable drying technology for the industrial-scale dehydration of *Wolffia globosa*.

#### **5. Conclusion**

This study evaluated and optimized drying technologies for *Wolffia globosa* using the Lean Six Sigma DMAIC framework. The conclusions of this research can be summarized according to the research objectives as follows. First, the drying performance of the selected drying methods—hot air drying (HAD), freeze drying (FD), and microwave vacuum drying (MVD)—was evaluated. The results showed that microwave vacuum drying achieved the fastest drying rate due to volumetric microwave heating combined with vacuum conditions, which significantly enhanced moisture removal compared with conventional convective drying. Second, the critical quality attributes of the dried products were analyzed, including water activity and color change. Freeze drying showed the best quality preservation with the lowest water activity ( $a_w < 0.25$ ) and the highest color retention. Hot air drying achieved the lowest  $\Delta E$  ( $3.01 \pm 0.27$ ) among the three methods, yet its 6× longer drying time compared with MVD limits its industrial applicability. Microwave vacuum drying resulted in moderate color change ( $\Delta E = 8.71 \pm 0.12$ ) but still maintained acceptable product quality. Third, the drying behavior and process efficiency were analyzed. Microwave vacuum drying significantly reduced drying time by approximately 80–90% compared with conventional tray drying while maintaining acceptable product stability. Finally, the Lean Six Sigma evaluation indicated that microwave vacuum drying provided the best balance between product quality, process efficiency, and process stability. Therefore, microwave vacuum drying can be considered the most suitable drying technology for the industrial-scale production of stable *Wolffia globosa* powder.

#### **References**

- Alibas, I., Energy consumption and colour characteristics of nettle leaves during microwave, vacuum and convective drying, *Biosystems Engineering*, vol. 96, no. 4, pp. 495-502, 2007.
- Antony, J., Readiness factors for the Lean Six Sigma journey in the higher education sector, *International Journal of Productivity and Performance Management*, vol. 63, no. 2, pp. 257-264, 2014.
- Barba, F. J., Parniakov, O., Pereira, S. A., Wiktor, A., Grimi, N., Boussetta, N., Saraiva, J., Raso, J., Lebovka, N. and Vorobiev, E. (2015). Current applications and new opportunities for the use of pulsed electric fields in food science and industry, *Journal of Food Engineering*, vol. 210, pp. 1-10, 2017.
- Bonazzi, C. and Dumoulin, E., Quality changes in food materials as influenced by drying processes, *Drying Technology*, vol. 29, no. 14, pp. 1561-1574, 2011.
- Chen, G. and Mujumdar, A. S., Drying of agricultural products: Fundamentals and applications, *Drying Technology*, vol. 26, no. 7, pp. 761-765, 2008.
- Datta, A. K., Porous media approaches to studying simultaneous heat and mass transfer in food processes, *Journal of Food Engineering*, vol. 80, no. 1, pp. 80-95, 2007.
- Deng, Y. and Zhao, Y., Effect of pulsed vacuum and ultrasound on dehydration of foods, *Journal of Food Engineering*, vol. 85, no. 1, pp. 84-93, 2008.
- Doymaz, I., Drying characteristics of food materials, *Food and Bioproducts Processing*, vol. 89, no. 1, pp. 31-38, 2011.
- Erbay, Z. and Icier, F., A review of thin layer drying of foods: theory, modeling, and experimental results, *Critical Reviews in Food Science and Nutrition*, vol. 50, no. 5, pp. 441-464, 2010.
- Fellows, P., *Food Processing Technology: Principles and Practice*, Woodhead Publishing, Cambridge, 2017.
- Feng, H., Yin, Y. and Tang, J., Microwave drying of food and agricultural materials: Basics and heat and mass transfer modeling, *Food Engineering Reviews*, vol. 4, no. 2, pp. 89-106, 2012.
- George, M. L., *Lean Six Sigma for Service: How to Use Lean Speed and Six Sigma Quality to Improve Services and Transactions*, McGraw-Hill, New York, 2005.

- Krokida, M. K., Maroulis, Z. B. and Saravacos, G. D., The effect of the method of drying on the color of dehydrated products, *International Journal of Food Science and Technology*, vol. 38, no. 1, pp. 53-59, 2003.
- Krokida, M. K. and Marinos-Kouris, D., Rehydration kinetics of dehydrated products, *Journal of Food Engineering*, vol. 57, no. 1, pp. 1-7, 2003.
- Kudra, T. and Mujumdar, A. S., *Advanced Drying Technologies*, CRC Press, Boca Raton, 2009.
- Kumar, M., Antony, J., Singh, R. K., Tiwari, M. K. and Perry, D., Implementing Lean Six Sigma in industries: A review, *International Journal of Productivity and Performance Management*, vol. 55, no. 7, pp. 491-505, 2006.
- Laureani, A. and Antony, J., Critical success factors for the effective implementation of Lean Six Sigma, *International Journal of Lean Six Sigma*, vol. 3, no. 4, pp. 274-283, 2012.
- Maskan, M., Kinetics of colour change of kiwifruits during hot air and microwave drying, *Journal of Food Engineering*, vol. 48, no. 2, pp. 169-175, 2001.
- Mayor, L. and Sereno, A. M., Modelling shrinkage during convective drying of food materials: A review, *Journal of Food Engineering*, vol. 61, no. 3, pp. 373-386, 2004.
- Montgomery, D. C., *Introduction to Statistical Quality Control*, John Wiley and Sons, New York, 2019.
- Mujumdar, A. S., *Handbook of Industrial Drying*, 4th Edition, CRC Press, Boca Raton, 2014.
- Mujumdar, A. S. and Law, C. L., Drying technology: Trends and applications in postharvest processing, *Drying Technology*, vol. 28, no. 12, pp. 1367-1386, 2010.
- Orsat, V., Changrue, V. and Raghavan, G. S. V., Microwave drying of fruits and vegetables, *Food and Bioproducts Processing*, vol. 85, no. 3, pp. 255-263, 2007.
- Rahman, M. S., *Food Properties Handbook*, CRC Press, Boca Raton, 2007.
- Ratti, C., Hot air and freeze drying of high-value foods: A review, *Journal of Food Engineering*, vol. 49, no. 4, pp. 311-319, 2001.
- Sagar, V. R. and Kumar, P. S., Recent advances in drying and dehydration of fruits and vegetables, *Journal of Food Science and Technology*, vol. 47, no. 1, pp. 15-26, 2010.
- Tang, J., Unlocking the potential of microwave processing in food industry, *Journal of Food Engineering*, vol. 146, pp. 1-3, 2015.
- Vega-Gálvez, A., Miranda, M., Díaz, L., Lopez, L., Rodriguez, K. and Di Scala, K., Effective moisture diffusivity determination and mathematical modelling of the drying curves of agricultural products, *Bioresource Technology*, vol. 100, no. 4, pp. 1357-1363, 2009.
- Wang, R., Zhang, M. and Mujumdar, A. S., Microwave vacuum drying of foods: A review, *Drying Technology*, vol. 32, no. 7, pp. 798-811, 2014.
- Zhang, M., Tang, J., Mujumdar, A. S. and Wang, S., Trends in microwave-related drying of fruits and vegetables, *Trends in Food Science and Technology*, vol. 17, no. 10, pp. 524-534, 2006.

## **Biographies**

**Phornpilat Senanok** is a master's student in the System Engineering program at the School of Industrial Engineering, Suranaree University of Technology. She graduated with a bachelor's degree in Animal Production Technology from Suranaree University of Technology in 2022. Currently, she is a researcher in Animal Technology and Innovation at Suranaree University of Technology. Her work focuses on the application of Lean Six Sigma for process improvement and quality optimization.

**Nara Samattapong** is Assistant Professor in School of Industrial Engineering, Suranaree University of Technology. He graduated with a Ph.D. in Mechatronics Engineering, Asian Institute of Technology in 2016, Focused Research are Simulation and Digital Twin Technology. Work address: School of Industrial Engineer, Institute of Engineering, Suranaree University of Technology, 111 University Road Suranaree Subdistrict, Muang District, Nakhon Ratchasima Province 30000.