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Evaluating the environmental sustainability of *Wolffia globosa* as a future food: A water footprint perspective on production systems

Jindawan Wibuloutai[1*], Nuchnapa Prathumchai[1], Saowalak Sutticharoen[1], Chuleewan Thunyasirinon[1], Supachai Sutticharoen[2]

[1] Faculty of Public Health, Mahasarakham University, Mahasarakham Province, Thailand
[2] Faculty of Technology, Mahasarakham University, Mahasarakham Province, Thailand
* Corresponding author's e-mail: jindawan.w@msu.ac.th

ABSTRACT

As global demand for sustainable protein rises, *Wolffia globosa* has emerged as a promising "future food." However, its environmental viability regarding water use remains under-researched. This study evaluated the water footprint (WF) of *W. globosa* across two production models in Thailand: an open natural pond and a controlled closed system, utilizing water footprint network standards and CROPWAT 8.0. Results showed a stark contrast in efficiency; the open system exhibited a high total WF of 1,615.62 m^3/ton due to significant evaporation and seepage. Conversely, the closed system demonstrated superior efficiency with a total WF of only 196.06 m^3/ton an 87.86% reduction. Furthermore, grey water footprints were nearly 50% lower in the closed system, reflecting enhanced nutrient management. Transitioning to closed-system models is essential to optimize water productivity and provide a scalable, sustainable pathway for aquatic protein production.

Keywords: *Wolffia globosa*, future food, water footprint, environmental sustainability, water-efficient agriculture.

INTRODUCTION

The global population is projected to reach 9.7 billion by 2050, significantly escalating the demand for high-protein food sources. Traditional agriculture currently consumes approximately 70% of global freshwater withdrawals, creating immense pressure on natural resources (Schyns et al., 2019). Under the constraints of climate change and planetary boundaries, transitioning toward sustainable "future foods" with low environmental impacts is critical (Steffen et al., 2015).

Wolffia globosa, the smallest flowering plant, has emerged as a promising sustainable protein source. It contains up to 40% protein (dry weight) and exhibits an exceptionally rapid doubling time, allowing for high biomass production in limited spaces (Sree et al., 2016). Despite its potential, research has primarily focused on its nutritional profile and growth rates. There is a significant research gap regarding its water use efficiency. This study fills this gap by providing a comprehensive water footprint (WF) assessment, comparing traditional natural ponds (Open System) with controlled environments (Closed System), to justify its viability as a sustainable food of the future.

The rapid growth of the global population, coupled with the intensifying impacts of climate change, has placed unprecedented pressure on food security and freshwater resources (Mekonnen and Hoekstra, 2016). As traditional agriculture consumes approximately 70% of global freshwater withdrawals, there is an urgent need to transition toward sustainable, high-protein alternative foods that require fewer resources (Postel et al., 1996; Steffen et al., 2015). In this context, *W. globosa*, commonly known as water meal, has emerged as a promising "future food" due to its exceptional nutritional profile, containing up to 40% protein, and its record-breaking growth rates (Appenroth et al., 2017; Ziegler et al., 2015).

Despite its potential, the environmental sustainability of *W. globosa* production, particularly its water resource intensity, remains a critical concern. Aquatic plant cultivation is inherently water-intensive, yet most research has focused on biomass yield and nutritional optimization rather than water use efficiency (Sree et al., 2016). The water footprint (WF) concept, developed by Hoekstra et al. (2011), provides a robust framework to quantify the total volume of freshwater used to produce a crop, categorized into green (rainwater), blue (surface/groundwater), and grey (pollution dilution) water footprints.

In Thailand, *W. globosa* has traditionally been cultivated in open natural ponds, where water loss through evaporation and seepage is high, and nutrient leaching often leads to water quality degradation (Prosridee et al., 2023; Pokpong, 2023). Furthermore, previous assessments of water intensity in Thai agricultural and industrial sectors have pointed out the need for localized data to manage water scarcity effectively, including production sectors that follow agriculture, such as handwoven silk production using silk threads from mulberry cultivation. The water footprint for this process is 1710 m³/ton, and the water footprint of one silk shirt was calculated backwards from the handwoven silk production process as 376 L (Wibuloutai et al., 2021). While transitioning to controlled closed systems in concrete tanks has been suggested to enhance hygiene and yield, a comprehensive comparative analysis of the water-environmental footprint between these two systems specifically for aquatic "superfoods" is still lacking in the existing literature (Phraongkul, 2024; Chuenwongarun and Naphatradonai, 2022). Therefore, this study aims to evaluate the environmental sustainability of *W. globosa* from a water footprint perspective. By comparing the green, blue, and grey WFs of open versus closed production systems, this research seeks to identify the most water-efficient pathway for scaling up this "superfood." The findings provide essential data for policymakers and sustainable agricultural planners to optimize water productivity while ensuring food security in tropical regions facing increasing water scarcity (Boulay et al., 2018; Schyns et al., 2019).

MATERIAL AND METHODS

The study utilized the CROPWAT 8.0 model to calculate evapotranspiration (ETc) and seepage (S). The Water Footprint assessment followed the global water footprint standard, categorizing water use into blue, green, and grey components.

Study sites and system characterization

The study was conducted in Thailand to compare two distinct cultivation models of *W. globosa*:

1. Open natural system: Cultivation in natural earthen ponds where the system is exposed to direct precipitation, evaporation, and soil seepage.
2. Closed system: Cultivation in concrete tanks equipped with managed water inputs, covering to prevent rainwater entry (for green WF isolation), and controlled water exchange.

Data collection and parameters

Primary data, including biomass yield (tons/ha/year), fertilizer application rates (kg/ha), and water exchange volumes, were collected through field surveys and farmer interviews. Meteorological data, including daily precipitation, maximum/minimum temperatures, and solar radiation, were obtained from the nearest weather stations to calculate reference evapotranspiration (T_0).

Water footprint calculation framework

The study compared an open system (earthen ponds) in Kalasin Province and a closed system (concrete tanks) in Mahasarakham Province. Data collection included biomass yield, fertilizer application rates, and meteorological data. The total water footprint (WFtotal) was calculated as the sum of green (rainwater), blue (surface/groundwater), and grey (pollution dilution) water components following the Water Footprint Network standard (Hoekstra et al. 2011). For blue water calculations, CROPWAT 8.0 was used to figure out evapotranspiration (ETc) and seepage (S). For grey water, nitrogen (N) leaching was used, with a maximum acceptable concentration (Cmax) of 5 mg/L based on the standards set by Thailand's Pollution Control Department.

The total water footprint (WFtotal) of *W. globosa* was calculated according to the water footprint network (WFN) standard (Hoekstra et al., 2011). The water footprint (WFtotal) of *W. globosa* was calculated as the sum of the green, blue, and grey water footprints:

$$WFtotal = WFgreen + \\ + WFblue + WFgrey \tag{1}$$

Green water footprint (WFgreen): WFgreen represents the volume of rainwater consumed by the crop. For the open system, it was calculated based on effective rainfall (Peff) using the CROPWAT 8.0 model:

$$WFgreen = \frac{10 \times \sum_{d=1}^{lgp} Peff}{Yield} \quad (2)$$

For the closed system with roofing, WFgreen was considered zero.

Blue water footprint (WFblue) includes evapotranspiration (ETc) and seepage (S) for open systems and evaporation plus water exchange (Wex) for closed systems.

$$WFblue, open = \\ = \frac{10 \times \sum \text{(ETc + S)}Peff}{Yield} \quad (3)$$

$$WFblue, closed = \frac{\sum \text{(ETc + Wex)}}{Yield} \quad (4)$$

Grey water footprint (WF_{grey}) calculated based on the nitrogen (N) leaching from fertilizers:

$$WFgrey = \frac{\propto \times AR \div Yield}{Cmax - Cnat} \quad (5)$$

where: α – leaching-run-off fraction (assumed 0.1 for closed, 0.25 for open system), *AR* – chemical application rate (kg/ha), *Cmax* – maximum acceptable concentration (5 mg/L for N, following Thailand's Pollution Control Department standards), *Cnat* – natural concentration in the receiving water body (assumed 0 mg/L).

Data analysis

All collected data were processed using IBM SPSS Statistics Version 26.0 (IBM Corp., Armonk, NY, USA). An Independent T-test was performed to evaluate the significant differences in water footprint components and biomass yield between the open pond and the closed system at a 95% confidence level ($p < 0.05$\$). Water quality parameters, including Nitrogen and Phosphorus, were measured using a Multiparameter Water Quality Meter (YSI ProPlus, YSI Inc., USA) to calculate the Grey Water Footprint accurately. All environmental data were calculated using CROPWAT 8.0 (FAO, Italy). Units across the study were standardized to m^3/ton to ensure international consistency and comparability.

RESULTS AND DISCUSSION

The analysis of the study results and the discussion of their significance are integrated to highlight the relationship between operational factors and environmental impacts.

Environmental characteristics and system performance

The meteorological conditions and operational parameters significantly influenced the water volume required for production. The specific cultivation processes and water use dynamics for the open natural pond system and the controlled closed system are illustrated in Figure 1 and Figure 2, respectively. The variability in the open system directly affected yield stability, even though average temperatures remained consistent across sites (Table 1).

The closed system achieved significantly higher biomass yields (10.0–18.50 ton/ha/cycle) compared to the open system (5–8.50 ton/ha/cycle). This difference is attributed to precise environmental control, reduced competition from other aquatic organisms, and consistent nutrient management using AB fertilizer. Furthermore, the protein content in the closed system reached 30–45%, reflecting optimal protein synthesis under controlled conditions, which aligns with findings that regulated nutrients and light are primary factors in enhancing the nutritional quality of Lemnaceae (Appenroth et al., 2017).

Comparative water footprint analysis

The total water footprint analysis revealed a massive disparity in efficiency. The total WF of the closed system (196.06 m^3/ton) was 87.86% lower than that of the open system (1,615.62 m^3/ton). The comparative breakdown of green, blue, and grey water components across both systems is summarized in Table 2 and visualized in Figure 3.

The high WFblue in the open system (1,003.50 m^3/ton) is primarily due to irrigation requirements needed to compensate for evaporation and seepage in earthen ponds. Although the vegetative mat of *Wolffia* can reduce evaporation (Zhang et al., 2019), the tropical climate still causes substantial losses. In contrast, the closed system reduced WFblue by 93.04% through the use of concrete tanks that eliminate seepage and enable water recycling.

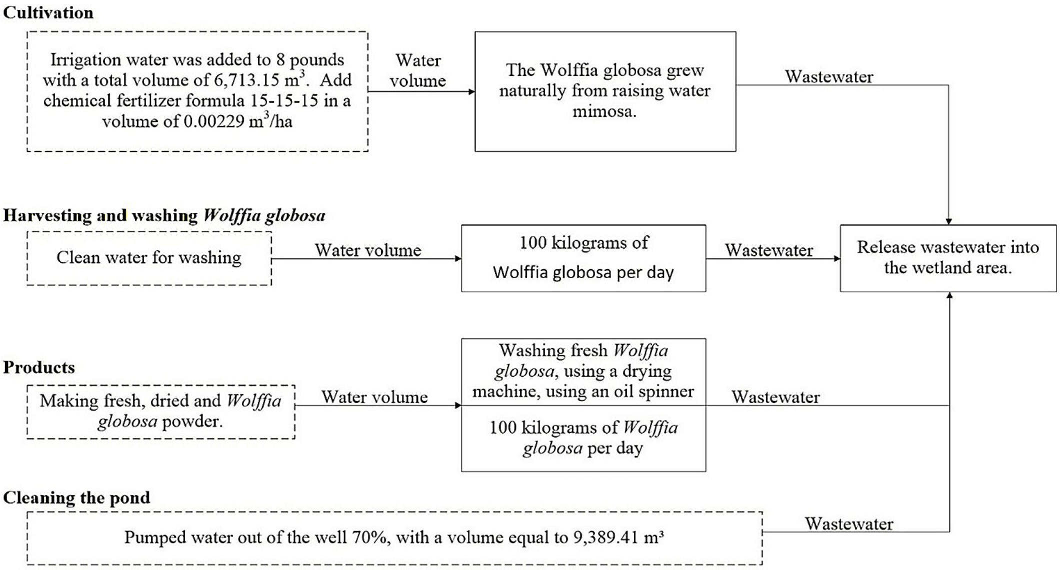

Figure 1. The process of *W. globosa* cultivation and water use in natural systems (open system)

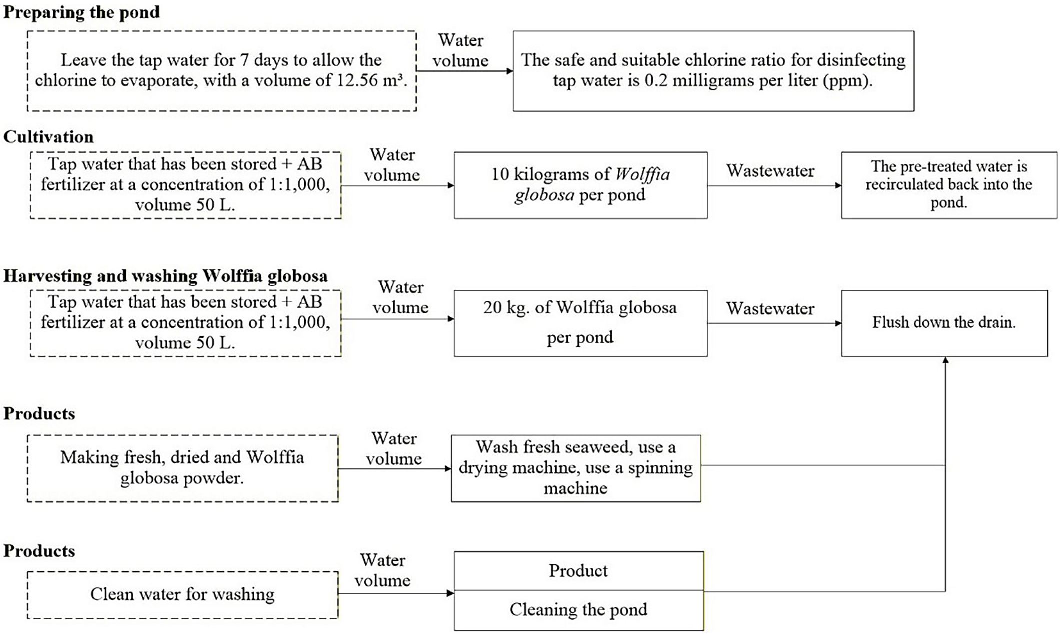

Figure 2. The process of *W. globosa* cultivation and water use in closed systems

Table 1. Environmental characteristics and operational parameters of the cultivation systems

Parameter	Unit	Open system (natural pond)	Closed system (Concrete tank)
Meteorological data			
Average temperature	°C	26.80 ± 12.10	28.2 ± 22.4
Total effective rainfall (Peff)	mm/cycle	663.80	709
Operational inputs			
Nitrogen application rate (AR)	kg/ha	0.80–1.50	0.50–1
Water exchange rate	m³/cycle	0.10–0.20	0.30–1
Yield performance			
Biomass yield	ton/ha/cycle	5–8.50	10–18.50
Protein content (dry basis)	%	15–28	30–45

Table 2. Comparative water footprint components of *W. globosa* production

Water footprint component	Open system (m^3/ton)	Closed system (m^3/ton)	Difference (%)	P-value
Green water (WFgreen)	361.40	0.00	-100%	<0.01**
Blue water (WFblue)	1,003.50	69.87	-93.04%	<0.01**
Grey water (WFgrey)	250.72	126.19	-49.67%	<0.05*
Total water footprint	1,615.62	196.06	-87.86%	<0.01

Note: * Significant at $p < 0.05$, ** Significant at $p < 0.01$.

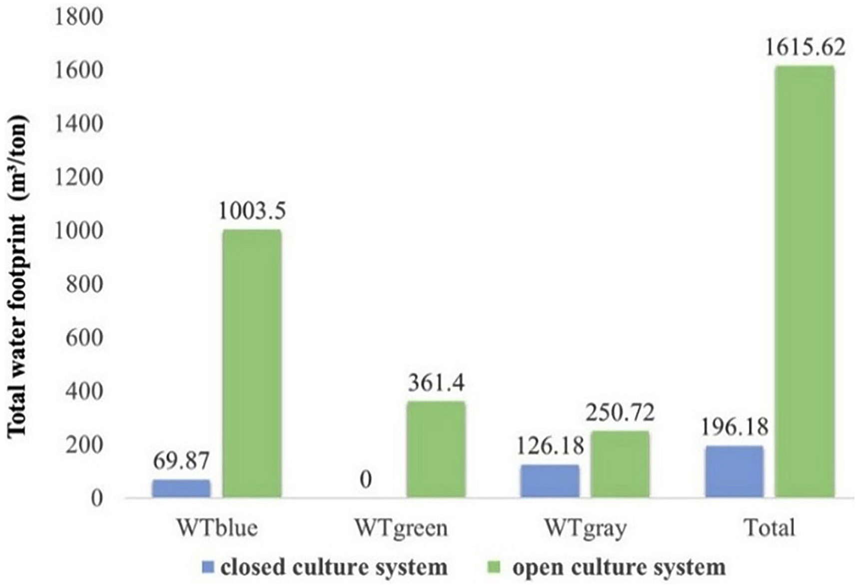

Figure 3. Comparison of the water footprint values (m^3/ton) for *W. globosa* cultivation in closed and open systems

WFgreen in the open system was 361.40 m^3/ton, reflecting rainwater utilization. In the closed system, this value was zero because roofing prevents rainwater entry to maintain nutrient stability and prevent contamination. While rainwater is a "free" resource, its unpredictability makes the open system vulnerable to climate shifts.

Grey water footprint and nutrient management

The WFgrey in the closed system (126.19 m^3/ton) was nearly 50% lower than in the open system (250.72 m^3/ton). This indicates that closed systems are far more efficient at nutrient retention. Open systems using N-P-K 15-15-15 fertilizers are prone to nitrogen leaching into natural water bodies (Deng et al., 2021). The closed system's ability to maintain nitrogen levels within the 5 mg/L threshold is critical for mitigating eutrophication (Franke et al., 2013).

Resource use efficiency and water productivity

Water productivity (WP) metrics confirm that transitioning to closed-loop technology is a high-value strategy for resource management. The WP of the closed system was 5.10 kg/m^3, over eight times higher than the open system's 0.62 kg/m^3 (Table 3).

The water-saving potential of 1,419.56 m^3/ton when shifting to a closed system is significant for sustainable agricultural planning. Compared to other products like handwoven silk, which has a water footprint of 1.710 m^3/ton, *W. globosa* in a closed system is a vastly more efficient source of protein (Wibuloutai et al. 2021).

Sensitivity analysis of the grey water footprint

Sensitivity analysis based on nitrogen leaching fractions (α) shows that open systems are

Table 3. Resource use efficiency and water productivity metrics

Metric	Unit	Open system	Closed system
Water productivity (WP)	kg/m³	0.62	5.10
Blue water efficiency	%	Low	High
Nutrient recovery efficiency	%	30–50	70–90
Water saving potential	m³/ton	-	1419.56

Table 4. Sensitivity analysis of grey water footprint based on nitrogen leaching fractions

Leaching fraction (α)	Open system WFgrey (m³/ton)	Closed system WFgrey (m³/ton)	Impact category
0.10 (Best Case)	100.29	126.19	Low pollution
0.15 (Moderate)	150.43	189.29	Moderate
0.25 (Baseline/Worst)	250.72	315.48	High pollution

highly sensitive to management errors. Even in the "worst-case" scenario for a closed system, the WFgrey remains more manageable than in the open system (Table 4). The drastic reduction in the blue water footprint in the closed system (93.04% reduction) is attributed to the use of concrete tanks, which eliminate soil seepage a major source of water loss in open natural ponds. Furthermore, the grey water footprint in the closed system was nearly 50% lower than in the open system (126.19 vs. 250.72 m^3/ton), demonstrating superior nutrient retention and minimal nitrogen leaching into the environment.

Industrial processing water footprint

When assessing the processing of *Wolffia* into ready-to-consume products (fresh, dried, or powder), the industrial sector water use must be considered. The closed-loop production process resulted in a product WF of 32 L/kg, while the open-loop process was slightly lower at 29.8 L/kg. The higher volume in the closed system is due to more rigorous washing protocols to maintain "superfood" hygiene standards. However, the 87.86% reduction in agricultural water use far outweighs this minor increase in processing water.

Strategic implications for sustainable food production

The transition from traditional *W. globosa* cultivation in natural ponds to controlled, closed systems is a key strategy for "Future Food" in Thailand, as it reduces the risk of biological and chemical contamination. Data indicates that upgrading cement pond technology to include recirculating aquatic systems (RAS) can further reduce the water footprint, bringing the production closer to a zero-discharge system.

W. globosa demonstrated a water productivity (WP) of 5.10 kg/m^3 in the closed system, which is significantly higher than typical protein crops like soybean or animal-based proteins. Compared to other local high-resource products such as handwoven silk (WF of 1.710 m^3/ton), the controlled cultivation of *W. globosa* represents a highly efficient pathway for protein production (Prosridee, 2023)

CONCLUSIONS

This study provides a comprehensive quantitative analysis of the water footprint associated with *W. globosa* cultivation. The findings confirm that while the open natural system is less capital-intensive, it results in high water consumption (1,615.62 m³/ton). The closed system emerges as a highly water-efficient alternative, reducing the blue water footprint by over 93% and the total water footprint by 87.86% (to 196.06 m³/ton) while maintaining high protein quality (30–45%). The reduction in the grey water footprint underscores its potential as an eco-friendly model. Transitioning to controlled systems is essential for scaling *Wolffia* as a sustainable global protein source. The study confirms that *W. globosa* is a water-efficient "future food" capable of scaling under resource-constrained conditions.

Agricultural policies should prioritize closed-system cultivation to maximize water efficiency and minimize nutrient-rich wastewater discharge

(Grey WF). Implementing water recirculation and onsite treatment technologies is essential to achieve a zero-discharge model. Future research should focus on optimizing nutrient recovery from effluent to ensure *Wolffia* production remains a sustainable and circular water management practice.

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