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Enhancing Resource Use Efficiency (RUE) in Indoor Vertical Farming Systems (PACER)

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Abstract

While indoor vertical farming systems provide substantial productivity, they necessitate rigorous resource management to prevent escalated operational costs and diminished sustainability. This study aims to systematically evaluate and optimize Resource Use Efficiency (RUE) within the PACER indoor farming facility at UTHM. The methodology encompasses comprehensive audits of water, energy, nutrients, and carbon dioxide consumption. System performance is quantified relative to crop yield utilizing the following indicators: Water Use Efficiency (WUE), Energy Use Efficiency (EUE), Nutrient Use Efficiency (NUE), and Carbon Dioxide Use Efficiency (CUE). Empirical findings indicate a WUE of 1.3052, an EUE of 0.1717, an NUE of 11.1935, and a CUE of 45.8351. These outcomes offer valuable insights into sustainable indoor cultivation practices, facilitating the advancement of highly efficient, controlled-environment agriculture.

1. Introduction

The escalating global demand for food is primarily driven by rapid urbanization, continuous population expansion, and the adverse effects of climate change. Projected demographic trends suggest the global population will reach approximately 9.7 billion by 2050, placing unprecedented strain on conventional agricultural systems to meet impending nutritional requirements [1]. Traditional agriculture, heavily dependent on arable land and optimal climatic conditions, is increasingly constrained by land scarcity, water deficits, and widespread environmental degradation [2]. Consequently, indoor vertical farming (IVF) has emerged as a viable, sustainable alternative for urban food production, accelerating the evolution of novel agricultural paradigms [3]. Indoor vertical farming (IVF), a specialized form of controlled environment agriculture (CEA), facilitates crop cultivation in vertically stacked layers within fully enclosed structures. This method employs advanced technologies to precisely regulate critical environmental parameters, including temperature, humidity, lighting, carbon dioxide concentration, and nutrient distribution [4]. Despite its advantages, IVF is often associated with higher operational costs due to intensive use of essential resources: water, energy, nutrients, and carbon dioxide.

To quantify this, Resource Use Efficiency (RUE) is utilized, commonly defined as the biomass or yield generated per unit of resource input [5]. RUE can be evaluated through individual performance indicators, which are Water Use Efficiency (WUE), Energy Use Efficiency (EUE), Nutrient Use Efficiency (NUE), and Carbon Dioxide Use Efficiency (CUE). All these indicators provide quantitative measures to assess system performance. While extensive literature exists on optimizing individual resources in CEA, comprehensive evaluations simultaneously analysing multiple resource efficiencies under empirical operating conditions remain scarce. Therefore, this research aims to systematically evaluate resource utilization within an operational IVF system. The primary objective is to quantify and analyse RUE across water, energy, nutrients, and carbon dioxide inputs. Secondary objectives include identifying critical parameters influencing RUE performance and proposing cost-effective strategies to enhance resource efficiency in indoor farming environments.

2. Methodology

2.1 System Description

The study was conducted at the Precision Agriculture in Controlled Environment Research (PACER) facility located at the Universiti Tun Hussein Onn Malaysia (UTHM). PACER is a container-based indoor vertical farming system operating under a controlled environment and utilizing a hydroponic cultivation method based on the Deep Flow Technique (DFT). Continuous crop production with regulated temperature, humidity, lighting, and carbon dioxide concentration is designed for the PACER system. In this study, Green Coral lettuce was selected as the test crop due to its short growth cycle, which is around a 25-day cycle estimation for PACER systems. Below is the figure of PACER.

Fig. 1 *PACER facility at UTHM*

2.2 Experimental Procedure

The experimental process covered a complete lettuce growth cycle from seed to harvest. Preparation, seeding, transplantation, and harvesting were the four primary phases of the agricultural process. To guarantee accurate data collection, all sensors and measurement devices were calibrated during the preparatory phase. During the seeding phase, the germination sponges were soaked in water at pH 6, then arranged in a tray for the next step. The seed is then placed into the sponge, and it is sprayed with water at pH 6 again until the required volume is reached. The tray will be sealed with black plastic to maintain humidity and temperature for seed germination. Fig. 2 shows the seed with a coating. Fig. 3 shows the seed placed into the germination sponge.

Fig. 2 *Coated seed from the Netherlands*

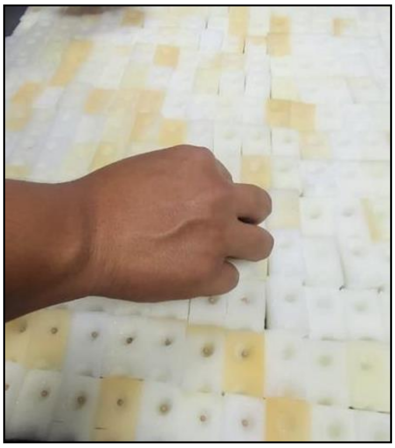

Fig. 3 *Seed placed into germination sponge*

After 2-3 days, the seed typically develops 2 leaves and will be ready to be put under the light for photosynthesis. After 14 days, 4 true leaves have grown, and the plants are ready to be transferred to the rack at PACER. Fig. 4 shows the seed after 3 days. Fig. 5 shows the plant after 14 days. Fig. 6 shows the plant placed into the growing pot. The process will be automatically handled by the PACER system. The resource audit will be started at the day the plant is transferred to the rack. In general, the audit will take the initial value of the resource before the start, the final value of the resource, and take the resources consumed for RUE analysis.

Fig. 4 *Seed after 3 days*

Fig. 5 *Seed after 14 days*

Fig. 6 *Sponge place to growing pot*

2.3 Resource Monitoring and Data Collection

Water, energy, nutrients, and carbon dioxide consumption were measured using a methodical audit-based approach. The first resource, water usage, was measured by recording the total amount of water supplied to the rack during the cultivation cycle. The initial amount of water will be zero, and as the water decreases, the amount refilled equals the water consumption. At last, the total amount of water refilled is added to get the water consumption. Fig. 7 shows the tank and the flowmeter used to measure water capacity. Next, the energy consumption was measured using electrical energy meters installed at the power distribution box. The initial value in kWh on the first day of the plant transfer at the rack will be recorded. Fig. 8 shows the meter installed in the distribution box.

Fig. 7 *Tank and Flowmeter*

Fig. 8 *Energy meter inside distribution box*

The total amount of nutrient solution supplied throughout the growth cycle was measured by recording the volume of nutrient A and B refilled to maintain the EC level of 850 ppm. Every refill will be recorded and summed together at the end of cultivation. Lastly, to collect data on carbon dioxide consumption, the tank's weight needed to be measured, and at the end of the cultivation cycle, the final tank weight will be recorded.

2.4 Resource Use Efficiency Indicators

Resource Use Efficiency (RUE) was evaluated using several performance indicators. Water Use Efficiency (WUE) was defined as the ratio of total water input to the fresh biomass yield. The equation was adopted from Ko and Piccinni et al. [6].

$$WUE = \frac{Y}{WI} \quad (1)$$

Energy Use Efficiency (EUE), Nutrient Use Efficiency (NUE), and CO_2 Use Efficiency (CUE) followed analogously:

$$EUE = \frac{PO}{EI} \quad (2)$$

$$NUE = \frac{Y}{NI} \quad (3)$$

$$CUE = \frac{Y}{CI} \quad (4)$$

These metrics evaluate individual resource effectiveness and identify inefficiencies within the system. The equation was adopted from Nazri & Pebrian et al. [7], Mandal et al. [8], Lim et al. [9], and Avgoustaki et al. [10]. A summary of these metrics is also provided in Fig. 9.

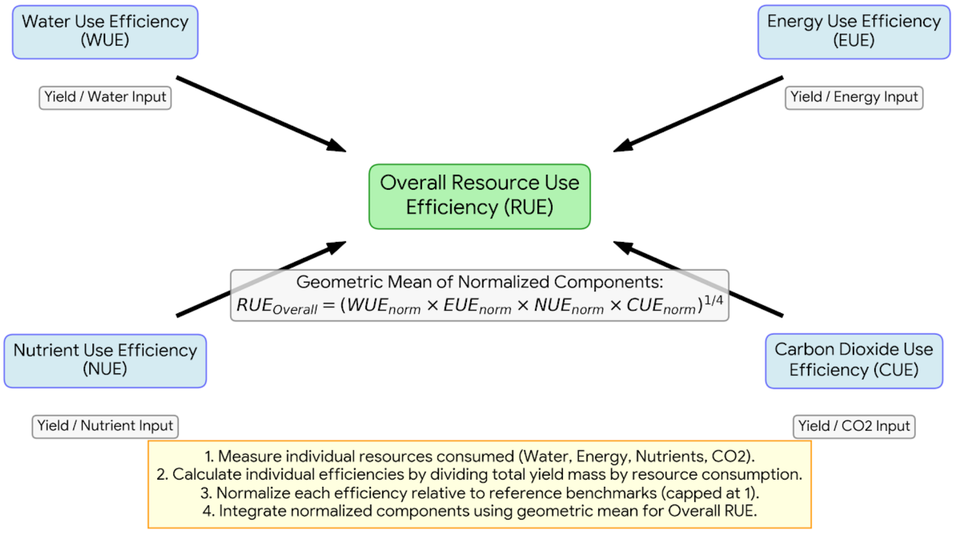

Fig. 9 *Relationship between Resource Use Efficiency (RUE) and its components*

2.5 Data Analysis

The data collected will be analysed to determine the relationship between resource inputs and crop yield. Each resource use efficiency will be adjusted using the min-max normalization method to enable equitable comparison and integration of various efficiency indicators with differing units and magnitudes. Therefore, all the individual resource use efficiencies will be between scale 0 and 1. The overall Resource Use Efficiency (RUE) will be calculated after the normalization step is done by using the geometric mean formulation as shown in equation 5. The equation was adopted from Han et al. [11]

$$RUE_{Overall} = (WUE^{norm} \times EUE^{norm} \times NUE^{norm} \times CUE^{norm})^{\frac{1}{4}} \tag{5}$$

The integrated RUE index was used to evaluate the indoor farming system's overall performance. Validated RUE overall against benchmarks highlights inefficiencies and allowed improvement for Malaysian indoor vertical farming.

3. Results and Discussion

3.1 Resource Consumption Profile

The resource consumption profile of the PACER indoor vertical farming system is evaluated over the entire plant growth cycle, which lasts approximately 25 days. The measured resources included in this case study are the primary inputs: water, energy, nutrients, and carbon dioxide. Table 1 shows the individual resource consumption for 25 day Lettuce cultivation cycle.

Table 1 *Individual resource consumption for 25 day cultivation cycle*

	Initial (day 0)	Final (day 25)	Consumption
Water Consumption (Litre)	35.5	61.2	25.7
Energy Consumption (kWh)	20,842.11	21,044.17	202.06
Nutrient Consumption (Litre)	5	8.1	3.1
Carbon Dioxide Consumption (kg)	20.516	19.754	0.762
Total Yield Mass (kg)		34.7	

Water consumption was mainly attributed to hydroponic solution replenishment and system losses. The water consumed for 25 day cycle is 25.7 litres. Energy consumption was dominated by artificial lighting and air conditioning, and it doesn't depend on plant growth. As shown in Table 1, the energy consumed for 1 cycle of cultivating lettuce is 202.06 kWh. Nutrient usage followed a consistent supply pattern throughout the growth cycle, while carbon dioxide consumption was regulated to maintain the desired concentration range for optimal plant growth.

3.2 Individual Resource Use Efficiency

Water Use Efficiency (WUE), Energy Use Efficiency (EUE), Nutrient Use Efficiency (NUE), and Carbon Dioxide Use Efficiency (CUE) were used to assess each resource use efficiency. Equations 1 through 5 were used. Table 2 shows individual resource use efficiency.

Table 2 *Individual resource consumption for 25 day cultivation cycle*

	Value	Unit
Water Use Efficiency (WUE)	1.3502	kg/L
Energy Use Efficiency (EUE)	0.1717	kg/kWh
Nutrient Use Efficiency (NUE)	11.1935	kg/L
Carbon Dioxide Use Efficiency (CUE)	45.5381	kg/kg CO_2

3.3 Normalized Resource Use Efficiency

All individual resource use efficiency values need to be standardized to a dimensionless scale to allow fair comparisons among efficiency indicators with different units and magnitudes. Normalization transforms the individual resource-use efficiency values in Table 2 relative to reference benchmarks from previous studies. Table 3 presents the reference benchmark values for WUE, EUE, NUE, and CUE. Table 4 shows the normalized WUE, EUE, NUE, and CUE.

Table 3 *Benchmark values for WUE, EUE, NUE, and CUE*

Indicator	Benchmark Value	Unit
WUE	0.14	kg FW $L^{-1}H_2O$
EUE	0.09	kg FW kWh^{-1}
NUE	102.6	kg FW $kg^{-1}N$
CUE	0.345	kg FW $kg^{-1}CO_2$

Note: Benchmark value adapted from Pennisi et al. [12] and Jia et al.[13]

Table 4 *Normalized efficiency of WUE, NUE, EUE, and CUE*

Indicator	Normalized Efficiency	Capped Normalized Efficiency
WUE	9.6443	1
EUE	1.9078	1
NUE	0.1091	0.1091
CUE	131.9945	1

A capped benchmark normalization was used to bound individual resource use efficiencies between 0 and 1. This approach is important to avoid dominance by any single resource; it allows comparability among resources with different units.

3.4 Overall Resource Use Efficiency

The overall resource use efficiency ($RUE_{Overall}$) was calculated by using the geometric mean of the normalized individual efficiencies. The use of this method ensures that poor performance in any single resource directly affects the overall RUE value. Equation 5 from before was used to determine overall resource use efficiency.

$$RUE_{Overall} = (WUE^{norm} \times EUE^{norm} \times NUE^{norm} \times CUE^{norm})^{\frac{1}{4}} \quad (5)$$

$$RUE_{Overall} = (1 \times 1 \times 0.1091 \times 1)^{\frac{1}{4}}$$

$$RUE_{Overall} = 0.5747$$

3.5 Discussion

Individual resource efficiencies for water (WUE), energy (EUE), nutrients (NUE), and carbon dioxide (CUE) were analysed relative to benchmark values from the literature. The PACER system demonstrated high performance in water, energy, and CO_2 utilization, as shown in Table 4. The results show that WUE is 9.6443, EUE is 1.9078, and CUE is 11.9945, indicating that the PACER system has high effectiveness in hydroponic water management, optimized artificial lighting and HVAC systems, and, lastly, better control of CO2 enrichment to support plant growth. The only downside is that NUE was considered lower than the benchmark, with a raw ratio of 0.11. This suggests that nutrient supply and uptake may not be fully optimized. This can lead to losses and fertilizer waste if it is not optimized quickly.

After applying capped benchmark normalization to standardize efficiencies, WUE, EUE, and CUE were all capped at 1 because their values exceed 1; NUE remained at 0.11. After normalization, it is fair to integrate the individual resources into one standard matrix. The resulting RUE of 0.5747 indicated the system has achieve 57% of the ideal composite resource use efficiency. It is concluded that even with high water, energy, and CO_2 efficiency, system productivity is constrained by nutrient efficiency.

4. Conclusion

This study provides a comprehensive evaluation of Resource Use Efficiency within the PACER indoor vertical farming system. Findings confirm that the facility exhibits exceptional proficiency in water, energy, and carbon dioxide management, with respective efficiencies substantially exceeding established literature benchmarks. However, the investigation identifies nutrient utilization as a significant operational bottleneck, recording performance metrics notably below the optimal threshold. The $RUE_{Overall}$ calculated using the geometric mean of capped normalized efficiencies is at 0.5747, which is equivalent to 57% of the ideal composite efficiency.

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Conflict of Interest

The authors declare that there is no conflict of interest regarding the publication of the paper.

Author Contribution

The authors solely conducted all aspects of this project, including study conception and design, data collection, analysis and interpretation of results, and draft manuscript preparation.

References

[1] United Nations, Department of Economic and Social Affairs, Population Division. (2022). World population prospects 2022: Summary of results. United Nations. Retrieved from: https://www.un.org/development/desa/pd/sites/www.un.org.development.desa.pd/files/wpp2022_summary_of_results.pdf

[2] Food and Agriculture Organization of the United Nations. (2009). How to feed the world in 2050. Retrieved from: https://www.fao.org/fileadmin/templates/wsfs/docs/Issues_papers/HLEF2050_Global_Agriculture.pdf

[3] Ehrmann, A. (2019). On the possible use of textile fabrics for vertical farming. Tekstilec, 62(1), 34–41. https://doi.org/10.14502/Tekstilec2019.62.34-41

[4] Miserocchi, L., & Franco, A. (2025). Benchmarking energy efficiency in vertical farming: Status and prospects. Thermal Science and Engineering Progress, 58, 103165. https://doi.org/10.1016/j.tsep.2024.103165

[5] Hodapp, D., Hillebrand, H. & Striebel, M. (2018). "Unifying" the concept of resource use efficiency in ecology. Frontiers in Ecology and Evolution, 6, Article 233. https://doi.org/10.3389/fevo.2018.00233

[6] Ko, J., & Piccinni, G. (2009). Corn yield responses under crop evapotranspiration-based irrigation management. Agricultural Water Management, 96(5), 799–808. https://doi.org/10.1016/j.agwat.2008.10.010

[7] Nazri, A. M., & Pebrian, D. E. (2017). Analysis of energy consumption in pineapple cultivation in Malaysia: A case study. Pertanika Journal of Science & Technology, 25(1), 17–28. http://www.pertanika.upm.edu.my/pjst

[8] Mandal, K. G., Saha, K. P., Ghosh, P. K., Hati, K. M., & Bandyopadhyay, K. K. (2002). Bioenergy and economic analysis of soybean-based crop production systems in central India. Biomass and Bioenergy, 23(5), 337–345. https://doi.org/10.1016/S0961-9534(02)00058-2

[9] Lim, M. Y., Kim, S. H., Roh, M. Y., Choi, G. L., & Kim, D. (2024). Nutrient dynamics and resource-use efficiency in greenhouse strawberries: Effects of control variables in closed-loop hydroponics. Horticulturae, 10(8), 851. https://doi.org/10.3390/horticulturae10080851

[10] Avgoustaki, D. D., & Xydis, G. (2020). How energy innovation in indoor vertical farming can improve food security, sustainability, and food safety? In M. J. Cohen (Ed.), Advances in Food Security and Sustainability (Vol. 5, pp. 1-51). Elsevier. https://doi.org/10.1016/bs.af2s.2020.08.002

[11] Han, J., Chen, J., Miao, Y., & Wan, S. (2016). Multiple Resource Use Efficiency (mRUE): A new concept for ecosystem production. Scientific Reports, 6, Article 37453. https://doi.org/10.1038/srep37453

[12] Pennisi, G., Gianquinto, G., Marcelis, L. F. M., Martin, M., & Orsini, F. (2025). Vertical farming: productivity, environmental impact, and resource use. A review. Agronomy for Sustainable Development, 45, Article 57. https://doi.org/10.1007/s13593-025-01055-w

[13] Jia, X., Speck, A., Feng, X., & Lee, C. W. (2025). Impact of water pH and cultivar on lettuce growth, water use efficiency, and nutrient use efficiency in deep water culture systems. Water, 17(17), Article 2637. https://doi.org/10.3390/w17172637