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ORIGINAL ARTICLE

# Productive aspects and operating costs of hydroponic lettuce under different nutrient solution flow rates

# Aspectos produtivos e custo operacional de alface hidropônica submetida a diferentes manejos de vazão da solução nutritiva

# Aspectos productivos y costo operativo de lechuga hidropónica sometida a diferentes manejos de flujo de la solución nutritiva

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## ABSTRACT

Producing leafy vegetables in intensive hydroponic systems requires knowledge of production cost variables and their proper management. Flow rate is a decisive factor in both production and operating costs as it directly affects energy consumption. This study aimed to assess the productive aspects of lettuce in relation to nutrient solution flow rate and energy consumption in a nutrient flow technique hydroponic system. The experiment was conducted on individual benches, with treatments consisting of five nutrient solution flow rates: 0.5; 1.0; 1.5; 2.0 and 2.5 liters per minute (L/min). Production components and water pump operating costs were assessed. Average plant production was 250.5, 282.75, 316, 338.5 and

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346.6 g for flow rates of 0.5, 1.0, 1.5, 2.0 and 2.5 L/min, respectively. The lowest operational energy costs and the highest production performance was observed at a flow rate of 1.5 L/min, while, reduced performance was noted at flow rates of 0.5 and 1.0 L/min. The different water management strategies evaluated indicate the feasibility of operating in a hydroponic system, considering all cost-benefit (C/B) ratios > 1.

**KEYWORDS:** *Lactuca sativa* L.; NFT; benefit-cost ratio.

## RESUMO

A produção de hortaliças em sistemas hidropônicos intensivos requer conhecimentos sobre as variáveis que compõem os custos de produção e seu manejo adequado. A vazão é um fator determinante, tanto nos custos de produção quanto nos custos operacionais, interferindo diretamente no consumo de energia elétrica. Este estudo teve como objetivo avaliar os aspectos produtivos da alface em relação à vazão da solução nutritiva e ao consumo de energia em um sistema hidropônico com técnica de fluxo de nutrientes. O experimento foi conduzido em bancadas individuais, com tratamentos compostos por cinco vazões de solução nutritiva de 0,5; 1,0; 1,5; 2,0 e 2,5 litros por minuto (L/min). Foram avaliados os componentes de produção e os custos operacionais da bomba d'água. A produção média das plantas foi de 250,5 g, 282,75 g, 316 g, 338,5 g e 346,6 g, para as vazões de 0,5 L/min, 1,0 L/min, 1,5 L/min, 2,0 L/min e 2,5 L/min, respectivamente. Os menores custos operacionais de energia e o maior desempenho produtivo foram observados na vazão de 1,5 L/min, enquanto o desempenho reduzido foi observado em vazões de 0,5 e 1,0 L/min. As diferentes estratégias de gerenciamento de água avaliadas indicam a viabilidade de operar um sistema hidropônico, considerando todas as relações custo-benefício (C/B) maiores que 1.

**PALAVRAS-CHAVE:** *Lactuca sativa* L.; NFT; relação custo-benefício.

## RESUMEN

La producción de hortalizas en sistemas hidropónicos intensivos requiere del conocimiento sobre las variables que componen los costos de producción y su correcto manejo. El caudal es un factor determinante en el costo de producción y operación del conjunto hidropónico, interfiriendo en el consumo de energía eléctrica. El objetivo de este trabajo fue evaluar aspectos productivos de lechuga rizada en relación al flujo de solución nutritiva y consumo de energía en un sistema hidropónico. El experimento se realizó en bancos individuales con tratamientos de cinco caudales de solución nutritiva: 0,5; 1,0; 1,5; 2,0 y 2,5 litros por minuto (L/min). Se evaluaron los componentes de producción y el costo operativo de activación del conjunto motobomba. La producción de la planta mostró promedios de 250.5 g, 282.75 g, 316 g, 338.5 g y 346.6 g, respectivamente para caudales de 0.5 L/min, 1.0 L/min, 1, 5 L/min, 2.0 L/min y 2.5 L/min. Se observaron menores costos de energía operativa y un mayor rendimiento de producción con un caudal de 1,5 L/min. El rendimiento productivo se redujo a caudales de 0,5 y 1,0 L/min. Los diferentes manejos del agua evaluados indican la factibilidad de operar en un sistema hidropónico, considerando todas las relaciones C/B > 1.

**PALABRAS CLAVE:** *Lactuca sativa* L.; NFT; relación costo-beneficio.

# 1 Introduction

Hydroponic techniques are an alternative to optimize resources such as cultivated areas, fertilizers, water, pesticides and specialized labor, resulting in superior production and quality (Martin; Molin, 2019; Goodman; Minner, 2019). The nutrient film technique (NFT) is one of the most common hydroponic methods and is widely used in Brazil, particularly for lettuce cultivation (Sausen *et al*., 2020).

Understanding the variables involved in production costs and their proper management is essential for achieving technical and financial benefits. Flow rate is a decisive factor in hydroponic production and operating costs, directly influencing energy consumption (Lei; Engeseth, 2021). This factor is crucial when selecting the pump assembly, as low flow rates require a more powerful system, impacting both energy and water savings and reducing the initial investment cost of a hydroponic project. If the nutrient solution circulates for longer periods and in greater volumes than necessary without improving productivity, energy consumption increases, which can account for up to 19.7% of total variable costs (Kannan *et al*., 2022).

The nutrient solution and its circulation regime should be established based on crop requirements and greenhouse design (Dalastra; Teixeira Filho; Vargas, 2020), considering the hydraulic system's characteristics, friction loss in pipes and accessories, as the total head height supplied by the water pump assembly. Several studies highlight the need for further research on the effects of flow rate in hydroponic systems for different leafy vegetables, with recommended rates ranging from 1.0 to 3.0 liters per minute per channel (Dalastra; Teixeira Filho; Vargas, 2020; Junior *et al*., 2008; Rezende *et al*., 2007). However, there is no consensus on the optimal nutrient solution flow rate for lettuce cultivation.

As such, the available methodologies for quantifying and adjusting nutrient solution flow to match productive capacity in different hydroponic setups are insufficient to establish more economical electrical energy practices in looseleaf lettuce production under an NFT system. This study aimed to assess the productive aspects of looseleaf lettuce in relation to nutrient solution flow rate and energy consumption in an NFT hydroponic system in the Alegrete region of Rio Grande do Sul state (RS), Brazil.

## 2 Material and Methods

The experiment was carried out in the Department of Vegetable Crops on the Alegrete Campus of the Farroupilha Federal Institute of Science, Education and Technology (IFFar). It took place in a greenhouse equipped with benches designed for NFT hydroponics, each with an individual hydraulics system.

The experimental setup consisted of five benches, each containing eight polypropylene NFT channels measuring 6 m long, 0.04 m on height and 0.08 m in width. The channels included 0.051 m wide inserts spaced 0.25 m apart. Each bench was equipped with a 250 L reservoir for the nutrient solution and a 0.5 hp peripheral water pump, as shown in Figure 1.

FIGURE 1 – Experimental setup inside the greenhouse.

Source: the authors (2022).

A completely randomized design was used, with treatments consisting of five nutrient flow rates: 0.5; 1.0; 1.5; 2.0 and 2.5 liters per minute (L/min), with one flow rate per channel. The benches received standard fertilization until harvesting, using a nutrient solution prepared with the granulated fertilizers Calcinit®, Kristalon® and Rexolin®. The chemical composition of the nutrient solution, along with reference values for electrical conductivity (EC) and pH is presented in Table 1. EC and pH were measured daily using a Hanna® portable pH/EV meter.

The circulation time for the nutrient solution was calibrated using timers, setting 15 minutes of nutrient circulation followed by a 30-minute rest period.

TABLE 1 - Description of the mineral composition of the nutrient solution used in the experiment.

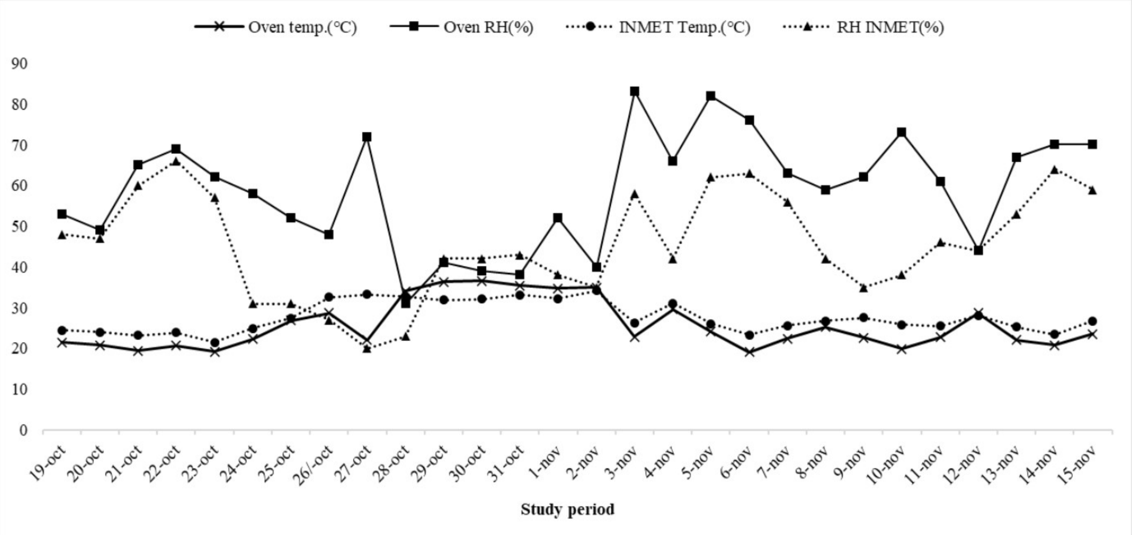
| EC | pH | N | $P_2O_5$ | $K_2O$ | $Ca^{2+}$ | $Mg^{2+}$ | $SO_4^{2-}$ | $Fe^{2+}$ |
|---|---|---|---|---|---|---|---|---|
| mS/cm³ | | ------------------------------ g/L ------------------------------ | | | | | | |
| 1.6 | 5.5 | 0.148 | 0.078 | 0.234 | 0.133 | 0.012 | 0.052 | 0.003 |

Source: the authors (2022).

A The lettuces used were ‘BS 55’ looseleaf, a variety that can be grown year-round in hydroponic systems and is resistant to mildew, lettuce mosaic virus (LMV) and leaf burn. The seedlings were produced from pelleted seeds grown in Carolina Soil® standard commercial substrate and transplanted to the hydroponic system benches upon the emergence of the fourth leaf.

Temperature and relative humidity in the greenhouse were recorded throughout the experiment using an Ambient Weather WS-1171 weather station and are presented in Figure 2. Local climate data were collected from an automated National Institute of Meteorology (INMET) A826 weather station, installed at the entrance to the IFFar experimental areas.

FIGURE 2 – Climate data recorded during the experimental period from October to November 2021.



Source: the authors (2022).

For analysis of the operating costs associated with running the water pump assembly, the dimensions of a commercial hydroponic setup were considered. This system consists of 24 benches, each containing eight 9-meter-long channels. Installed in a greenhouse measuring 40 meters in length and 8 meters in width, the system has a total head (Th) of 3 meters, which accounts for the sum of the pump's head height and friction loss, as measured by a manometer installed at the pump outlet.

Water horsepower (WHP) was determined by the equation: $WHP = \frac{Q\ (L/s) \times Th\ (m)}{75}$, where Q is the flow rate in liters per second, Th is the total head expressed in meters, and 75 is the conversion factor of Kgf.m/s into horsepower (hp). Pump efficiency of 52% was considered.

Energy consumption was calculated considering a 28-day production cycle, totaling 336 hours of pump operation. The cost per kWh was determined according to the regional electric utility company's rates for October 2022, in compliance with the Brazilian Electricity Regulatory Agency (ANEEL) and state taxes.

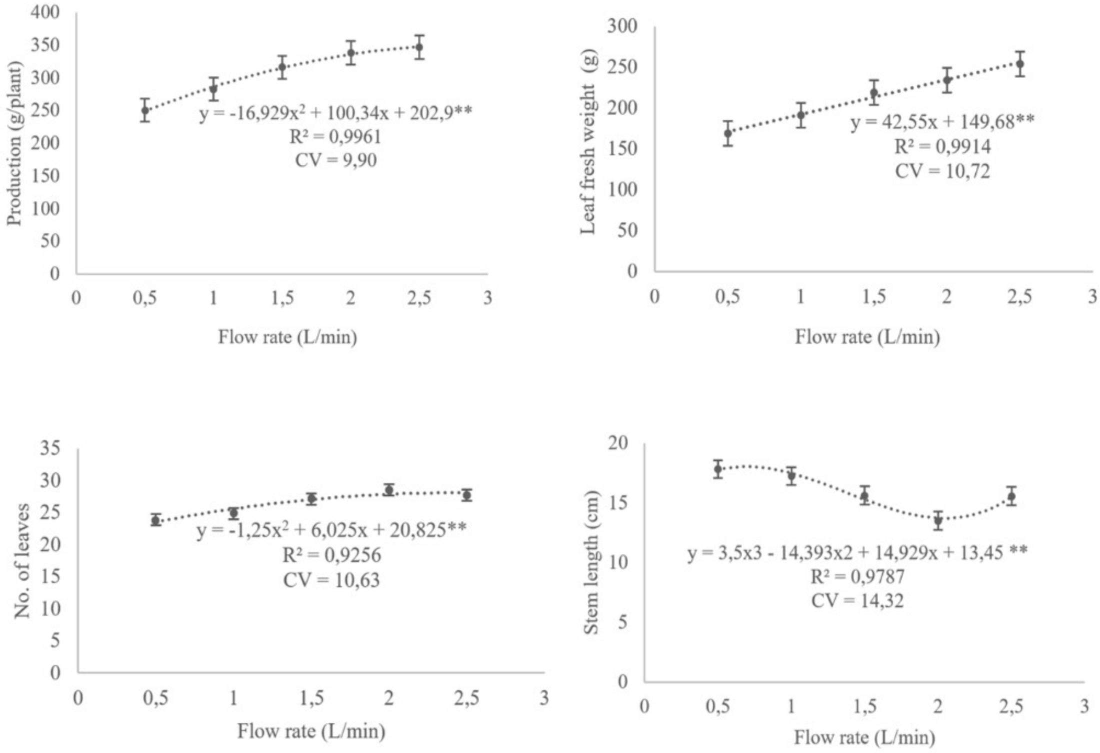
Harvesting was performed 28 days after transplanting (DAT). Ten plants from each treatment were assessed for the following variables: production (g/plant), plant height (cm), number of leaves, stem length (cm), leaf fresh weight (g) and leaf dry weight (g/100g).

Drying was conducted in a forced-air oven at 60 °C for 72 hours to determine total, root and shoot dry weight. Data were subjected to analysis of variance ($\alpha$=0,05) and regression. Statistical analysis was performed using the SISVAR software (Ferreira, 2020).

## 3 Results and Discussion

The analysis of variance showed a significant difference in production data, number of leaves, fresh leaf mass and stem length. These variables were subjected to regression analysis, as illustrated in Figure 3. However, no statistically significant difference was observed for plant height and leaf dry mass.

FIGURE 3 – Results for production, leaf fresh weight, number of leaves, and stem length of lettuce under different nutrient flow rates.



Source: the authors (2022).

Superior production results were obtained at 2.5 L/min. However, excess nutrient solution or depth greater than 4 mm in the channel may justify the longer root length, as reported by Dalastra; Teixeira Filho; Vargas (2020).

Considering marketing standards for lettuce, factors such as the number of leaves (NL) and leaf fresh weight (LFW) are particularly noteworthy. The lowest NL was recorded at a flow rate of 0.5 L/min, with an average of 23.8 leaves per plant, while the highest average, 28.5 leaves per plant, was observed at 2.0 L/min.

The number of leaves is related to leaf fresh weight. However, as reported by Djidonou and Leskovar (2019), LFW may also be influenced by the ions concentration of the nutrient solution, with better performance possible under greater nutrient availability rather than being solely dependent on the solution flow rate.

Regarding stem length, greater elongation was observed at the lowest nutrient solution flow, with a reduction as flow increased. Some authors report that stem elongation occurs under stress conditions promoted by the cultivation environment and is strongly related to high temperatures and water deficit (Majid *et al*., 2020; Casey *et al*., 2022). It is important to consider that resistance to bolting is a key attribute for leafy vegetables, as stem elongation precedes floral structure development, interfering with the commercial quality of these plants.

The prediction of energy consumption and operational costs for activating the motor-pump set at the experimental flow rates proposed in this study is presented in Table 2.

TABLE 2 – Operational cost analysis of motor pump system activation for hydroponic system, considering different nutrient solution flow rates.

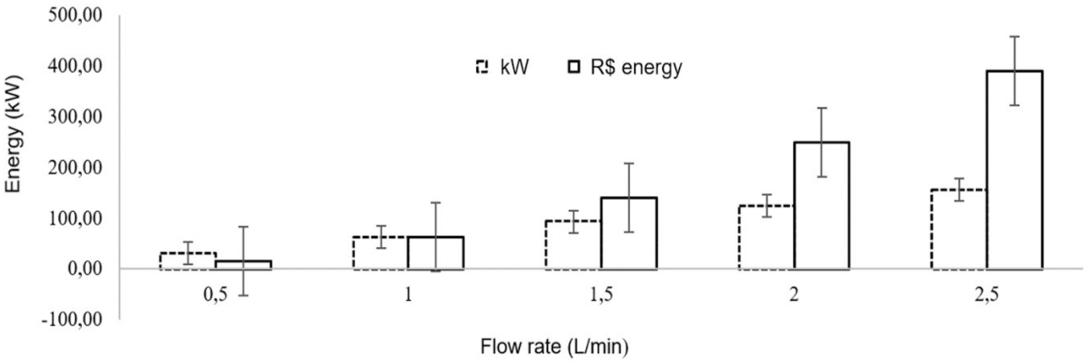
| Required flow rate | | | Calculated power | | Commercial model | | Estimated operating costs | | |
|---|---|---|---|---|---|---|---|---|---|
| Q/channel (L/min) | Q tot (L/min) | Q tot (L/s) | WHP (hp) | Power pe (hp) | hp | kW | kW | BRL/ cycle | BRL/m$^2$ |
| 0.50 | 96.00 | 1.600 | 0.085 | 0.126 | 0.50 | 0.37 | 31.20 | 25.90 | 0.08 |
| 1.00 | 192.00 | 3.200 | 0.171 | 0.253 | 0.50 | 0.37 | 62.40 | 51.80 | 0.16 |
| 1.50 | 288.00 | 4.800 | 0.256 | 0.379 | 0.50 | 0.37 | 93.61 | 77.69 | 0.24 |
| 2.00 | 384.00 | 6.400 | 0.341 | 0.505 | 1.00 | 0.75 | 124.81 | 103.59 | 0.32 |
| 2.50 | 480.00 | 8.000 | 0.427 | 0.631 | 1.00 | 0.75 | 156.01 | 129.49 | 0.40 |

Q= flow rate; L/min= liters per minute; L/s= liters per second; WHP= hydraulic power; pe= pump efficiency; hp= horse power; kW= kilowatt; BRL= Brazilian Real.
Source: the authors (2022).

The data show that the energy required, and operating costs remained the same at flow rates of 0.5, 1.0 and 1.5 L/min. However, productive performance varied, with the lowest production observed at 0.5 and 1.0 L/min.

From 2.0 L/min onwards, the power required doubled, and energy costs increased proportionally. Figure 4 illustrates the potential for resource savings and equipment optimization within the ideal working ranges, according to technical specifications.

FIGURE 4 – Evolution of water pump operating costs according to different flow rates in the hydroponic system.



Source: the authors (2022).

Benefit-cost ratios (BCR) for different selling formats are presented in Table 3. Seasonality and price fluctuation throughout the year are characteristics of the vegetable market. In this study, the selling format influenced profitability, with BCR values for the different flow rates investigated.

TABLE 3 – Analysis of the benefit-cost ratio for the commercialization of hydroponic lettuce grown under different nutrient solution flow rates.

| Q (L/min) | kW | BRL energy | Selling by weight | | | | | Selling by count | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Prod (Kg) | kg/m² | BRL/m² | BRL/320m² | BCR | Prod/m² | BRL/un | BRL/m² | BRL/320m² | BCR |
| 0.5 | 31.20 | 15.60 | 0.25 | 4.50 | 6.75 | 2160.00 | 138.45 | 18.00 | 1.50 | 27.00 | 8640.00 | 553.81 |
| 1 | 62.40 | 62.40 | 0.28 | 5.08 | 7.61 | 2436.48 | 39.04 | 18.00 | 1.50 | 27.00 | 8640.00 | 138.45 |
| 1.5 | 93.61 | 140.41 | 0.32 | 5.69 | 8.53 | 2730.24 | 19.44 | 18.00 | 1.50 | 27.00 | 8640.00 | 61.53 |
| 2 | 124.81 | 249.62 | 0.34 | 6.08 | 9.13 | 2920.32 | 11.70 | 18.00 | 1.50 | 27.00 | 8640.00 | 34.61 |
| 2.5 | 156.01 | 390.02 | 0.35 | 6.23 | 9.34 | 2989.44 | 7.66 | 18.00 | 1.50 | 27.00 | 8640.00 | 22.15 |

Q= flow rate; L/min= liters per minute; kW= kilowatt; Prod= production; BRL= Brazilian Real; BRC= Benefit-cost ratios.

Source: the authors (2022).

The energy cost (kW and BRL energy) rises exponentially, from 15.60 BRL at 0.5 L/min to 390.02 BRL at 2.5 L/min. Production per square meter (kg/m²) increases initially but stabilizes, with marginal gains observed at higher flow rates. For example, at 0.5 L/min, production is 4.50 kg/m², and at 2.5 L/min, it only increases to 6.23 kg/m², despite the sharp increase in energy consumption. This suggests diminishing returns on production as energy costs increase with higher flow rates. The inefficiency at elevated flow rates highlights a key consideration for hydroponic systems: optimizing the trade-off between energy input and production gains.

The BCR declined proportionally to the increase in energy required by the system. It is important to note that the BCR depends on the selling format adopted for produce (by weight or count), since this impacts profitability and varies between different states and municipalities (Souza; Gimenes; Binotto, 2019; Gumisiriza *et al.*, 2022). Therefore, local commercial classification standards should be considered to ensure optimal profitability.

The vegetable market is characterized by price fluctuations and seasonality, which directly impact revenue. The selling-by-count format mitigates some of this risk by providing stable pricing per unit, whereas selling by weight is subject to price variability and potential losses during market lows. However, both formats demonstrate that profitability is highest at lower flow rates, where energy costs are minimal relative to revenue. Higher flow rates, while providing slight production gains, fail to justify the corresponding increase in energy expenditure.

Under the experimental conditions assessed, flow rates of 0.5 and 1.0 L/min do not comply with the acceptable weight and size requirements for commercialization. In contrast 1.5, 2 and 2.5 L/min resulted in greater production but required proportionally higher energy expenditure. Therefore, the 1.5

L/min flow rate can be considered the most economical, providing superior production and quality results.

The different water management strategies demonstrate the operational feasibility of the hydroponic system, with BCRs > 1. However, the selection of the circulation regime is closely tied to product quality and market value.

This study shows that the sizing of the motor pump set, the operational management, and the flow rate adjustment in this production system influence the productive and economic parameters of hydroponic lettuce cultivation. However, further studies are needed to explore the savings generated by different combinations of nutrient solution circulation time throughout the day and across seasons. This will help identify management strategies that are both technically efficient and economically viable.

## 4 Conclusion

Flow rates of 0.5 and 1.0 L/min resulted in lower productive performance for lettuce and are not recommended for commercial production.

Flow rates of 1.5, 2.0 and 2.5 L/min promoted better productive performance in lettuce plants across different selling formats.

A flow rate of 1.5 L/min enabled electricity savings of 51% when compared to 2.0 and 2.5 L/min.

In addition to operational aspects, recommendations for the optimal flow rate should account the commercialization conditions imposed by the local market.

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