Ciências Agrárias
SEMINA

DOI: 10.5433/1679-0359.2025v46n6p1917

Optimal economic water regime for cowpea production

Regime hídrico ótimo econômico para a produção do feijão-caupi

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Highlights

Adequate water availability increases cowpea productivity.
Severe water deficit limits cowpea economic return.
Irrigation is a viable agricultural technique for cowpea production.

Abstract

Rational irrigation management maximizes crop productivity, optimizes water-use efficiency as a production factor, and enhances economic indicators in irrigated areas. In this study, we determined the optimal economic water regime for cowpea production using economic indicators. The experiments were conducted at the Empresa Brasileira de Pesquisa Agropecuária experimental area in Teresina, PI, Brazil in 2021 and 2022. The treatments consisted of five irrigation depths, which were calculated as percentages of crop evapotranspiration and cumulative rainfall. Irrigation regimes were 227.90, 241.10, 274.40, 300.80, and 318.40 mm·cycle^{-1} in 2021 and 133.80, 191.70, 249.00, 303.00, and 357.00 mm·cycle^{-1} in 2022. Irrigation management operations accounted for the largest share of total and effective operational costs. Rainfall reduced electricity and irrigation management costs, particularly in 2021. Regimes exceeding 274.40 mm·cycle^{-1} (2021) and 249.00 mm·cycle^{-1} (2022) increased yield, gross revenue, total and effective operational profits, benefit/cost ratio, profitability index, and break-even price, despite higher total and effective production costs. The regimes of 300.80 mm·cycle^{-1} (2021) and 303.00 mm·cycle^{-1} (2022) were demonstrated to be the most economically viable for cowpea production.

Key words: Conventional sprinkler irrigation. Economic analysis. Economic coefficients. Irrigation management. Production costs.

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Received: Apr. 02, 2025 Approved: Jan. 13, 2026

Resumo

O manejo racional da irrigação é uma ferramenta fundamental para maximizar a produtividade das culturas agrícolas, otimizar a eficiência de uso da água como fator de produção e, melhorar os índices econômicos das áreas irrigadas. O objetivo deste estudo foi determinar o regime hídrico ótimo econômico para a produção do feijão-caupi, baseado em indicadores econômicos. Os experimentos foram conduzidos na área experimental da Empresa Brasileira de Pesquisa Agropecuária em Teresina-PI, Brasil, nos anos de 2021 e 2022. Os tratamentos foram cinco lâminas de irrigação, calculadas a partir de percentuais da evapotranspiração da cultura, somadas à precipitação pluviométrica acumulada no período. Os regimes hídricos corresponderam a 227,90; 241,10; 274,40; 300,80 e 318,40 mm por ciclo (2021) e 133,80; 191,70; 249,00; 303,00 e 357,00 mm por ciclo (2022). As operações de manejo da irrigação foi o componente de produção com maior participação nos custos operacionais total e efetivo. A ocorrência da precipitação pluviométrica contribuiu para minimizar os custos de energia elétrica e das operações de manejo da irrigação, especialmente no ano de 2021. Regimes hídricos superiores a 274,40 e 249,00 mm por ciclo em 2021 e 2022, respectivamente, incrementaram a produtividade, a receita bruta, os lucros operacionais total e efetivo, e otimizaram a relação benefício/custo, o índice de lucratividade e o preço de equilíbrio, porém apresentaram aumentos dos custos operacionais total e efetivo de produção. Os regimes hídricos 300,80 e 303,00 mm por ciclo foram os mais economicamente viáveis para a produção do feijão-caupi cultivado nos anos de 2021 e 2022, respectivamente.

Palavras-chave: Análise econômica. Coeficientes econômicos. Custo de produção. Irrigação por aspersão convencional. Manejo da irrigação.

Introduction

Cowpea (*Vigna unguiculata*) is one of the most widely produced and commercialized crops in northern and northeastern Brazil. It holds substantial socioeconomic importance because it generates employment and income (J. S. de Silva Jr. et al., 2020). Cultivation occurs under both rainfed and irrigated conditions (Carvalho et al., 2023).

Rational irrigation management determines exact irrigation depth required by the crops and optimal timing of application. This approach maximizes crop yield, optimizes the efficiency of water and fertilizer usage as production factors, and improves economic indicators in irrigated areas (L. S. Pereira et al., 2019, 2023; Carvalho et al., 2023). Cowpea water requirement ranges from 290 to 350 mm·cycle^{-1} depending on the cultivar, climate, and soil conditions (J. S. de Silva Jr. et al., 2020; Munjonji & Ayisi, 2021).

Economic analysis was calculated using various coefficients, such as operational costs, gross revenue, operational profits, benefit-cost ratio, profitability index, break-even yield, and break-even price to achieve maximum profit (Martin et al., 1994; Gomes et al., 2013). Thus, rational and effective use of available resources aims to achieve the highest economic returns (Monteiro et al., 2006). Controlling production costs is essential because of the narrow profitability margins of most crops (Barbosa et al., 2014).

Economic analysis not only assesses the viability of agricultural production system but also identifies optimal systems and irrigation management strategies (Vieira et al., 2011; Barbosa et al., 2014; Dias et al., 2021; Carvalho et al., 2023). Irrigation depths that yielded maximum productivity in melon and cowpea lacked economic viability (Monteiro et al., 2006; Ramos et al., 2012). This highlights the need for economic studies to determine irrigation depths that maximize profitability.

Understanding of the connection between crop yield and irrigation depths is essential to maximize financial returns in irrigated areas. This study aimed to determine the optimal economic water regime (WR) for cowpea production based on economic indicators.

Material and Methods

Experiments were conducted at the Empresa Brasileira de Pesquisa Agropecuária (EMBRAPA Meio-Norte) experimental area (05°05′ S, 42°48′ W, 74.4 m) in Teresina, PI, Brazil from September to November 2021 (A1) and July to September 2022 (A2). The conditions of the A1 and A2 experiments were the following: mean air temperature of 29.85°C and 28.58°C; relative humidity of 61.41% and 57.78%; reference evapotranspiration (ETo) of 4.27 mm·day^{-1} and 4.48 mm·day^{-1}; and cumulative rainfall 174.00 mm and 13.2 mm (Figure 1).

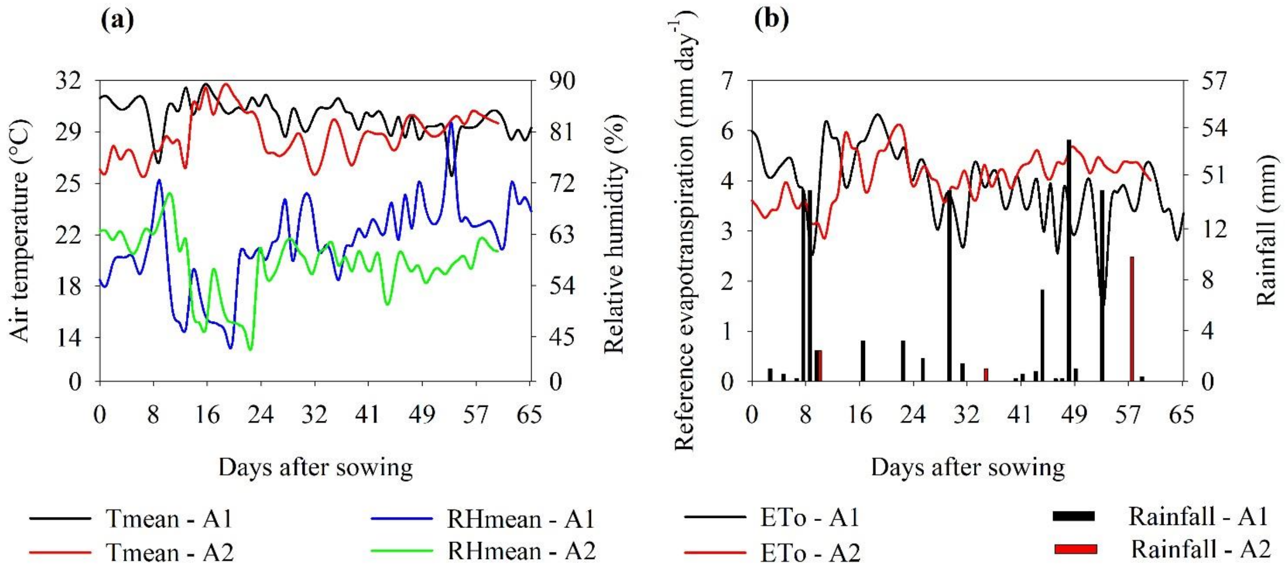

Figure 1. Daily means of the meteorological variables mean air temperature (Tmean) and mean relative air humidity (RHmean) (a), reference evapotranspiration (ETo) and rainfall (b), observed during the experimental periods of 2021 (A1) and 2022 (A2).

Soil in the experimental area was classified as a sandy loam Yellow Argissol. For the A1 and A2, the chemical properties at 0–0.20 m depth were the following: pH (H_2O) = 6.1 and 5.7; Ca^{2+} = 1.63 and 0.78 $cmol_c·dm^{-3}$; Mg^{2+} = 0.41 and 0.35 cmolc·dm^{-3}; K^+ = 0.21 and 0.09 $cmol_c·dm^{-3}$; Na^+ = 0.03 and 0.02 $cmol_c·dm^{-3}$; Al^{3-} = 0.04 and 0.04 $cmol_c·dm^{-3}$; H + Al = 1.41 and 1.69 $cmol_c·dm^{-3}$; P (Melich) = 33.65 and 31.12 mg·dm^{-3}; organic matter = 14.3 and 12.9 g·kg^{-1}; CECt = 3.69 and 2.94 $cmol_c·dm^{-3}$; and base saturation (V) = 61.78 and 42.32%. The physical-hydraulic properties of the experiments were the following: sand = 876.5 g·kg^{-1}; silt = 37.5 g·kg^{-1}; clay = 86.0 g·kg^{-1}; bulk density = 1.50 g·cm^{-3}; field capacity (θcc) = 0.217 $m^3·m^{-3}$; and permanent wilting point (θpmp) = 0.05 $m^3·m^{-3}$.

Conventional harrowing was used for soil preparation in both years. Basal fertilization and soil chemical analysis were conducted according to Melo et al. (2018). At sowing, a fertilizer with an $N:P_2O_5:K_2O$ ratio of 5:30:15 was applied at 30, 20, and 60 kg·ha^{-1}.

Cowpea cultivar BRS Inhuma planted at a spacing of 0.5 m´ 0.10 m achieved a density of 200,000 plants·ha^{-1}. This study used a randomized block design with four replicates. Treatments consisted of five irrigation depths (WDn) that were determined daily from crop evapotranspiration (ETc) fractions [50, 75, 100, 125, and 150% ETc for the A1 and 40, 70, 100, 130, and 160% ETc for the A2]. Total water regimes (WDn + rainfall) were 227.90, 241.10, 274.40, 300.80, and 318.40 mm·$cycle^{-1}$ for the A1 and 133.80, 191.70, 249.00, 303.00, and 357.00 mm·$cycle^{-1}$ for the A2.

Water was applied using a conventional sprinkler with a spacing of 12 m ´ 12 m at a flow rate of 1.76 $m^3·h^{-1}$ and service pressure of 245,16 kPa. Sixteen collectors with a spacing of 3.0 ´ 3.0 m in central plot quadrants was used to measure the WDn after each irrigation.

The ETo-based irrigation management was estimated using the Penman–Monteith equation (Allen et al., 1998). Crop Coefficient (Kc) values reported by Bastos et al. (2008) was used. Fixed two-day irrigation interval was applied to WDn, 50% in the morning and 50% in the afternoon. WDn variations started at 21 and ended at 55 days after sowing (DAS), respectively.

Harvesting was manually performed at 65 DAS for the A1 and 60 DAS for A2. Grain yield (GY; kg·ha^{-1}) was adjusted to a moisture content of 13% (J. S. de Silva Jr. et al., 2020). Water use efficiency (WUE; kg·m^{-3}) was calculated as GY (kg·ha^{-1}) divided by (WDn + rainfall; m^3) (J. S. de Silva Jr. et al., 2020). The GY and WUE data were subjected to ANOVA and regression analysis using R v. 4.2.3 (R Foundation for Statistical Computing, Vienna, Austria). All statistical analyses were performed at a 5% significance level.

Economic analysis, accounting for the total operational production cost (TOC) and effective operational cost (EOC), was performed using market quotations (Table 1). Input, service, equipment prices, and sales values for 2021 and 2022 were obtained at exchange rates of R$ 5.55 and R$ 5.23 per USD, respectively.

Table 1
Components of cowpea production costs in the years 2021 and 2022

Year 2021 (A1)					
Item	(US$ ha^{-1})	WR (mm per cycle)	Ni	EC (US$ ha^{-1})	Ci (US$)
Inputs (a)	188.75	WR1: 227.90	8	3.24	79.28
Mech. Ops. (b)	119.82	WR2: 241.10	9	4.04	89.19
Labor (c)*	128.83	WR3: 274.40	11	6.04	109.01
Irrig. system (d)	1,763.81	WR4: 300.80	12	7.63	118.92
CD	11.29	WR5: 318.40	14	8.69	138.74
		WRY: 310.91	13	8.24	128.83
		WRE: 288.23	12	6.87	118.92
Year 2022 (A2)					
Item	(US$ ha^{-1})	WR (mm por ciclo)	Ni	EC (US$ ha^{-1})	Ci (US$)
Inputs (a)	228.97	WR1: 133.80	15	11.28	172.08
Mech. Ops. (b)	144.36	WR2: 191.70	15	16.59	172.08
Labor (c)*	149.14	WR3: 249.00	15	21.84	172.08
Irrig. system (d)	2,142.79	WR4: 303.00	15	26.84	172.08
CD	15.43	WR5: 357.00	15	31.74	172.08
		WRY: 311.00	15	27.53	172.08
		WRE: 236.36	15	20.68	172.08

Mech. ops.: mechanized agricultural operations; Irrig. system: irrigation system for 1 ha; Ni: number of irrigation management operations; EC: electricity cost; CD: annual depreciation of the irrigation system; Ci: cost of irrigation water application (Ci = Ni × daily labor rate); WRY: water regime corresponding to the estimated maximum yield in the year; WRE: water regime corresponding to the estimated maximum water use efficiency in the year; *: does not include EC and Ci costs.

The EOC included inputs (seeds, fertilizers, and insecticides), mechanized operations (land preparation, sowing, fertilization, internal transport, and threshing), labor (weeding, irrigation management, phytosanitary treatment, and harvesting), and electricity (Gomes et al., 2013). The TOC was calculated according to Martin et al. (1994). The EOC was determined by materials (quantity´ unit price), mechanized operations (machine-hour rates), and labor (man-days ´ regional wages).

A linear method of capital replacement was used for capital depreciation (CD; Table 1) owing to physical or economic wear (Vilas Boas et al., 2011). According to the Companhia Nacional de Abastecimento [CONAB] (2020) methodology, for a conventional sprinkler systems, the residual value ranges between 20% and 30.302% and the useful life is 20 years. Analysis period matched cycle durations, which are 0.16 years or the A1 and 0.18 years for A2.

Electricity cost (EC) was calculated according to M. E. M. Pereira et al. (2018). For both the A1 and A2, electricity was charged by EQUATORIAL (Piauí distributor) at a rural tariff of USD 0.086 per 0.131 kWh^{-1}. The EC values varied, and they were WDn-dependent (Table 1).

The profitability of the irrigation treatment was analyzed using the following economic coefficients (Martin et al., 1994): gross revenue (RB), total operational profit (TOP), effective operational profit (EOP), break-even yield (PROE), and break-even price (PE). Benefit-cost (B/C) ratio and profitability index (IR) were analyzed according to Gomes et al. (2013). According to the CONAB (2022), sales prices for the A1 and A2 were 64.8 and 55.3 USD per 60-kg sack, respectively.

Results and Discussion

WR significantly influenced cowpea's GY in the A1 and A2. The fitted quadratic polynomial equations resulted in determination coefficients of 0.88 for the A1 and 0.98 and for the A2. These models explained > 85% of the GY variations. The maximum estimated GY value of 1,513.71 $kg \cdot ha^{-1}$ occurred at the WR of 310.91 $mm \cdot cycle^{-1}$ in the A1 while the maximum estimated GY value of 1,620.00 $kg \cdot ha^{-1}$ occurred at 311.00 $mm \cdot cycle^{-1}$ in the A2 (Table 2).

Table 2
Yields, operational costs, gross revenue, and total operating profit of cowpea cultivated under water regimes in the years 2021 and 2022

Year 2021						
WR mm per cycle	GY kg ha^{-1}	P_T sc ha^{-1}	WUE kg m^{-3}	EOC US$ ha^{-1}	TOC US$ ha^{-1}	RB US$ ha^{-1}
WR1	780.66	13.01	0.33	519.92	531.21	842.79
WR2	995.24	16.59	0.40	530.63	541.92	1,074.44
WR3	1,371.87	22.86	0.50	552.45	563.74	1,481.04
WR4	1,502.82	25.05	0.50	563.95	575.24	1,622.41
WR5	1,507.75	25.13	0.46	584.83	596.12	1,627.74
WRY	1,513.71	25.23	0.49	574.47	585.76	1,634.17
WRE	1,458.96	24.32	0.51	563.19	574.48	1,575.06
Regression equations						
GY= -0.106362*x²+66.1397*x-8768.30 R2= 0.88 WUE= -0.000051**x²+0.0294**x-3.72 R2= 0.80						
Year 2022						
WR mm per cycle	GY kg ha^{-1}	PT sc ha^{-1}	WUE kg m^{-3}	EOC US$ ha^{-1}	TOC US$ ha^{-1}	RB US$ ha^{-1}
WR1	600.00	10.00	0.47	705.84	721.26	553.42
WR2	1,140.00	19.00	0.47	711.14	726.57	1,051.50
WR3	1,500.00	25.00	0.46	716.40	731.83	1,383.55
WR4	1,620.00	27,00	0.46	721.39	736.82	1,494.24
WR5	1,560.00	26.00	0.45	726.30	741.73	1,438.89
WRY	1,620.00	27.00	0.46	722.08	737.51	1,494.24
WRE	1,440.00	24.00	0.52	715.24	730.67	1,328.21
Regression equations						
GY= -0.032454**x²+20.1870**x-1556.62 R2= 0.98 WUE= -0.000011**x²+0.0052**x-0.09 R2= 0.99						

* and ** indicate significance at 0.05 and 0.01, respectively, by Student's t-test; R^2: coefficient of determination; WRY: water regime corresponding to the estimated maximum yield in the year; WRE: water regime corresponding to the estimated maximum water use efficiency in the year.

Crop productivity is a key economic indicator of cultivated areas. Water availability significantly affects crop productivity (L. S. Pereira et al., 2023). Depending on cultivar, a WR < 260 mm·cycle^{-1} reduces GY to < 1,000 kg·ha^{-1} (Souza et al., 2020). If water is sufficient, photosynthesis, vegetative growth, and cowpea productivity are enhanced (J. de S. Silva et al., 2021; Carvalho et al., 2023). Under such condition, optimum yield of 1,474.1–1,850 kg·ha^{-1} can be achieved (S. Silva et al., 2019; Carvalho et al., 2023).

In this study, WR significantly affected WUE in both years. For the A1 and A2, maximum estimated WUE values of 0.51 and 0.52 kg·m^{-3} occurred at the WRs of 288.23

and 236.36 mm·cycle^{-1}, respectively (Table 2). WUE indicates water economy of irrigated agricultural land (Elhady et al., 2021). WUE declines with increasing WR as GY lags added water volume. The reduced water is a production factor (L. S. Pereira et al., 2019). Therefore, irrigation strategies must balance productivity and water use to minimize percolation and evaporation losses. The WUE values of BRS Tumucumaque were < 0.58 kg·m^{-3} at a WR of 288.70 mm·cycle^{-1} (J. S. de Silva Jr. et al., 2020). These variations were plausibly caused by the difference in cultivar genetics and productivity.

The average labor costs for the A1 occupied 43.31% of the EOC and 42.45% of the TOC while the average labor costs for the A2 occupied 44.81% of the EOC and 43.86% of the TOC, respectively. The operational cost of irrigation management dominated both the EOC and TOC (Table 2). Therefore, although all costs warrant reduction strategies, prioritizing the operation cost of irrigation management is essential. Rational irrigation costs must be integrated into the analysis of total production (Zamberlan et al., 2011). These results is different from those of Carvalho et al. (2023), which showed that inputs had the largest operational cost share in cowpea production. The differences were likely caused by different payment strategies for irrigation management used in the two studies.

The WR5 of the A1 showed the highest EOC of 584.83 USD·ha^{-1} while the WR5 of the A2 showed the highest EOC of 726.30 USD·ha^{-1} (Table 2). The EOC represents a short-term producer outlay (Dias et al., 2021; Barbosa et al., 2014). A higher WDn increases irrigation, irrigation management, and electricity costs (EC), thus elevating EOC. Greater amount of rainfall in 2021 lowered these costs, consequently reducing the EOC and TOC (Figure 1b; Table 2).

Operational costs encompass all crop-cycle expenses (Tsunechiro et al., 1995). Operational and capital costs are critical for the economics of irrigated areas (El-Hassan et al., 2015). Carvalho et al. (2023) observed that higher WDn raised cowpea's TOC to 526.48 USD·ha^{-1} in 2015 and 522.06 USD·ha^{-1} in 2016. In the A1 and A2, the average CDs were 1.99 and 2.11% of the TOC, respectively, underlining the importance of fixed asset accounting. Although CD covers replacement of capital that are physically worn or obsolete (Vilas Boas et al., 2011), producers often exclude CD; this action is harmful for crop productivity (Sabbag & Nicodemo, 2011).

A lower WR reduces RB. The WR1 and the WR2 yielded the lowest RB values in both years (Table 2). The range of RB for the A1 was 842.79–1,634.17 USD·ha^{-1} while that of the A2 was 553.42–1,494.24 USD·ha^{-1}. The RB reflects the financial gain at set prices per sack produced (Martin et al., 1994). Lower GY and sack quantity (QP) reduced RB in the WR1 and WR2 (Table 2). Carvalho et al. (2023) also reported that RB declined under water restriction to 650–1,042.78 USD·ha^{-1} in 2015 and 650–1,517.20 USD·ha^{-1} in 2016. RB variations were likely caused by differences in production costs and market prices.

Water restriction limits cowpea physiology, vegetative growth, and grain filling and causes flower and pod abortion in legumes (J. de S. Silva et al., 2021; Fang et al., 2010). Consequently, GY and QP are reduced. A lower QP reduces profits as RB is lower than TOC (Carvalho et al., 2023).

Total operational profit (TOP) and effective operational profit (EOP) were positive for all the WR of the A1 (Table 3). In the A2, the WR1 yielded negative TOP (-167.84 USD·ha^{-1}) and EOP (-152.41 USD·ha^{-1}). The overall TOP and EOP were higher in the A1. TOP and EOP values indicate long- and short-term viabilities, respectively (Gomes et al., 2013). Therefore, negative TOP and EOP values indicate that RB is insufficient to cover the costs, indicating losses. Gomes et al. (2013) and Carvalho et al. (2023) observed that profit declined under water stress in bean and cowpea productions.

Table 3

Operating profits, benefit–cost ratio, profitability index, break-even yields, and break-even prices of cowpea cultivated under water regimes in the years 2021 and 2022

Year 2021							
WR mm per cycle	TOP US$ ha^{-1}	EOP US$ ha^{-1}	B/C	IR %	PROE sc ha^{-1}	PROE kg ha^{-1}	PE US$ sc^{-1}
WR1	311.58	322.87	1.62	36.97	8.20	467.97	40.83
WR2	532.53	543.82	2.02	49.56	8.37	477.40	32.67
WR3	917.30	928.59	2.68	61.94	8.70	496.63	24.66
WR4	1,047.18	1,058.46	2.88	64.54	8.88	506.76	22.97
WR5	1,031.62	1,042.91	2.78	63.38	9.20	525.15	23.72
WRY	1,048.41	1,059.70	2.84	64.16	9.04	516.02	23.22
WRE	1,000.58	1,011.87	2.80	63.53	8.87	506.09	23.63
Year 2022							
WR mm per cycle	TOP US$ ha^{-1}	EOP US$ ha^{-1}	B/C	IR %	PROE sc ha^{-1}	PROE kg ha^{-1}	PE US$ sc^{-1}
WR1	-167.84	-152.41	0.78	-30.33	13.03	781.97	72.13
WR2	324.93	340.36	1.48	30.90	13.13	787.72	38.24
WR3	651.73	667.16	1.93	47.11	13.22	793.42	29.27
WR4	757.42	772.85	2.07	50.69	13.31	798.84	27.29
WR5	697.17	712.60	1.98	48.45	13.40	804.15	28.53
WRY	756.73	772.16	2.07	50.64	13.33	799.58	27.32
WRE	597.54	612.97	1.85	44.98	13.20	792.16	30,44

WRY: water regime corresponding to the estimated maximum yield in the year; WRE: water regime corresponding to the estimated maximum water use efficiency in the year.

In the A1, the range of B/C ratio was 1.62–2.88. In the A1, the WR4 and the maximum WR yield (WRY) achieved the highest B/C ratio of 2.88 and 2.84, respectively. The A2 had a lower B/C ratio compared with the A1 and the lowest B/C ratio of 0.78 occurred in the WR1 (Table 3). Lower GY levels reduced both RB and B/C ratio. Gomes et al. (2013) observed a similar decline in the B/C ratio of common bean production under water-stress condition. B/C ratio guides economic decisions, with value < 1 indicating production loss (Gama, 1990; Gomes et al., 2013).

In this study, water restriction lowered the IR in both years. However, only the WR1 of the A2 showed a negative IR (-30.33%). IR shows the profit proportion of RB after costs (Sabbag & Nicodemo, 2011). Apart from the WR1 of the A2, all WR had the IR > 30%, indicating profitability. Despite the higher GY and RB values in the WRY treatment (Table 2), they did not maximize IR or B/C ratio (Table 3). Carvalho et al. (2023) confirmed that water restriction during cowpea production in BR3-Tracuateua resulted in the IR of 21–65%, suggesting that the gains were attributed to the increased yield and TOP.

Break-even yield (PROE) increased in parallel with WR. The WR5 of the A1 reached the highest PROE of 9.20 sc·ha^{-1}, an increase of 10.86% from the WR1 and 9.02% from the WR2. The WR5 of the A2 achieved the maximum PROE of 13.40 sc·ha^{-1} (Table 3). The WR1 yield of the A2 was 10.0 sc·ha^{-1}, which matched the average yield of the Piauí cowpea of 6.58 sc·ha^{-1} (CONAB, 2022); however, it was lower than the PROE (13.03 sc·ha^{-1}), which was the minimum value to cover the costs (Gomes et al., 2013).

The WR1 showed the highest break-even price (PE) of 40.83 USD·sc^{-1} for the A1 and 72.13 USD·sc^{-1} for the A2 (Table 3). The WR1 of the A2 exceeded the CONAB price of 55.3 USD per 60-kg sack, indicating that the production was not viable. PE is the minimum price that covers operational costs (Gomes et al., 2013).

Higher sack production in the A1 and A2 caused lower PE in the WR3, WR4, WR5, and WRY and the maximum WR of the WUE. Higher irrigation depths raise costs but boost yields, causing revenue to exceed the costs and lower the costs per production unit (Gerlach et al., 2013).

The WR3 (100% ETc) of the A1 achieved a PE of 24.66 USD·sc^{-1} while the WR3 of the A2 achieved a PE of 29.27 USD·sc^{-1} (Table 3). These values exceed those obtained in the previous study by Carvalho et al. (2023) for BR3-Tracuateua at 100% ETc, which were 19.61 and 21.43 USD·sc^{-1}. The variation in the PE was presumably caused by the difference in exchange rates and operational costs.

These results highlight the effects of water regimes on cowpea productivity, economic efficiency, and rational water use. Economic indicators, such as GY, WUE, TOP, B/C, IR, PROE, and PE, provides a guidance for choosing irrigation strategies that have balanced costs and returns. These findings support sustainable irrigation policies, technology adoption incentives, producer training, and water-saving practices in water-scarce regions.

Conclusions

Increasing water regime generally promotes economic gains in cowpea production. However, the WR of 133.80 mm·cycle⁻¹ used in 2022 resulted in low productivity and economic indicators; therefore, it should not be used for future cowpea production. The WRs of 300.80 and 303.00 mm·cycle⁻¹ were the most economically viable for cowpea production in 2021 and 2022, respectively.

References

Allen, R. G., Pereira, L. S., Raes, D., & Smith, M. (1998). *Crop evapotranspiration: guidelines for computing crop water requirements.* FAO. (Irrigation and Drainage Paper, 56).

Barbosa, R. M., Homem, B. F. M., & Tarsitano, M. A. A. (2014). Custo de produção e lucratividade da cultura do amendoim no município de Jaboticabal, São Paulo. *Revista Ceres, 61*(4), 475-481. doi: 10.1590/0034-737X201461040005

Bastos, E. A., Ferreira, V. M., Silva, C. R. da, & Andrade, A. S. de, Jr. (2008). Evapotranspiração e coeficiente de cultivo do feijão-caupi no Vale do Gurguéia, Piauí. *Irriga, 13*(2), 182-190. doi: 10.15809/irriga.2008v13n2p182-190

Carvalho, E. D. O., Costa, D. L., Luz, D. B. D., Rua, M. L., Velame, M. D. L., Monteiro, A. C., Vieira, I. C. D. O., Pinto, J. V. D. N., Fernandes, G. S. T., Nunes, H. G. G. C., Souza, P. J. D. O. P., & Santos, M. A. dos. (2023). Economic indicators for cowpea cultivation under different irrigation depths. *Revista Brasileira de Engenharia Agrícola e Ambiental, 27*(8), 618-624. doi: 10.1590/1807-1929/agriambi.v27n8p618-624

Companhia Nacional de Abastecimento (2022). *Acompanhamento da safra brasileira de grãos: primeiro levantamento safra 2020/21 e 2021/22.* CONAB. https://www.conab.gov.br/info-agro/safras/graos/boletim-da-safra-de-graos/item/download/39390_421561554638ce988f258fd7094dea73

Companhia Nacional de Abastecimento (2020). *Norma metodologia do Custo de produção 30.302: Sistema de Operações Subsistema de Gestão de Informações e Conhecimento, SUINF/GECUP.* CONAB. https://www.conab.gov.br/images/arquivos/normativos/30000_sistema_de_operacoes/30.302_Norma_Metodologia_de_Custo_de_Producao.pdf

Dias, O., Silva, P., Piedade, A., Souza, P., & Ramirez, G. (2021). Produtividade e custo operacional efetivo de uma propriedade rural da Rede de Fazendas Alfa do Agrihub. *Agrarian Academy, 8*(16), 56-69. doi: 10.18677/Agrarian_Academy_2021B6

Elhady, S. A. A., El-Gawad, H. G. A., Ibrahim, M. F., Mukherjee, S., Elkelish, A., Azab, E., Gobouri, A. A., Farag, R., Huda, A. Ibrahim, H. A., & El-Azm, N. A. (2021). Hydrogen peroxide supplementation in irrigation water alleviates drought stress and boosts growth and productivity of potato plants. *Sustainability, 13*(2), 899. doi: 10.3390/su13020899

El-Hassan, W. H. A., El-Kassar, G., Fujimaki, H., Kitamura, Y., & Khater, A. (2015). Assessment of cost-effective alternatives for improving irrigation systems in the Nile Delta. *Irrigation and Drainage, 64*(4), 454-463. doi: 10.1002/ird.1931

Fang, X., Turner, N. C., Yan, G., Li, F., & Siddique, K. H. (2010). Flower numbers, pod production, pollen viability, and pistil function are reduced and flower and pod abortion increased in chickpea (*Cicer arietinum* L.) under terminal drought. *Journal of Experimental Botany, 61*(2), 335-345. doi: 10.1093/jxb/erp307

Gama, C. D. (1990). A relação benefício-custo como critério de projecto em engenharia geotécnica. *Geotecnia, (58),* 31-40. doi: 10.14195/2184-8394_58_3

Gerlach, G. A. X., Arf, O., Corsini, D. C. D. C., Silva, J. C. D., & Coletti, A. J. (2013). Análise econômica da produção de feijão em função de doses de nitrogênio e coberturas vegetais. *Pesquisa Agropecuária Tropical, 43*(1), 42-49. doi: 10.1590/S1983-40632013000100005

Gomes, E. P., Jordan, R. A., Motomiya, A. V. D. A., Padua, J. B., Biscaro, G. A., & Geisenhoff, L. O. (2013). Análise econômica e viabilidade energética da cultura do feijoeiro comum sob irrigação. *Revista Brasileira de Engenharia Agrícola e Ambiental, 17*(8), 835-842. doi: 10.1590/S1415-43662013000800006

Martin, N. B., Serra, R., Antunes, J. F. G., Oliveira, M. D. M., & Okawa, H. (1994). Custos: sistema de custo de produção agrícola. *Informações Econômicas, 24*(9), 97-122.

Melo, F. D. B., Cardoso, M. J., Bastos, E. A., & Ribeiro, V. Q. (2018). *Recomendação de adubação e calagem para o feijão-caupi na região Meio-Norte do Brasil.* EMBRAPA. http://www.infoteca.cnptia.embrapa.br/infoteca/handle/doc/1101331

Monteiro, R. O. C., Colares, D. S., Costa, R. N. T., Leão, M., & Aguiar, J. V. D. (2006). Função de resposta do meloeiro a diferentes lâminas de irrigação e doses de nitrogênio. *Horticultura Brasileira, 24*(4), 455-459. doi: 10.1590/S0102-05362006000400012

Munjonji, L., & Ayisi, K. K. (2021). Leaf gas exchange and δ13C in cowpea and triticale under water stress and well-watered conditions. *Heliyon, 7*(5), e07060. doi: 10.1016/j.heliyon.2021.e07060

Pereira, L. S., Saad, J. C., Cardoso, A. I. I., Silva, M. A., Lima, C. J. G. S., & Silva, E. M. (2023). Intermittence in irrigation management and nitrogen optimize yield and water use efficiency in baby lettuce. *Spanish Journal of Agricultural Research, 21*(4), 1-13. doi: 10.5424/sjar/2023214-20482

Pereira, L. S., Silva, E. M. D., Ferreira, J. O. P., Santos, V. L. G., Lima, C. J. G. S., & Silva, G. B. D., Jr. (2019). Watermelon yield and efficiency of use of water and nitrogen. *Caatinga, 32*(3), 769-777. doi: 10.1590/1983-21252019v32n321rc

Pereira, M. E. M., Lima, J. A. D., Jr., Lima, V. M., Gusmão, S. A. L. de, Oliveira, P. D. de, & Silva, A. L. P. da (2018). Viabilidade econômica da produção de couve-flor irrigada por gotejamento no Nordeste Paraense. *Revista de Ciências Agrárias, 61*(1), 1-8. doi: 10.22491/rca.2018.2738

Ramos, H. M. M., Bastos, E. A., Andrade, A. S. D., Jr., & Marouelli, W. A. (2012). Estratégias ótimas de irrigação do feijão-caupi para produção de grãos verdes. *Pesquisa Agropecuária Brasileira, 47*(4), 576-583. doi: 10.1590/S0100-204X2012000400014

Sabbag, O. J., & Nicodemo, D. (2011). Viabilidade econômica para produção de mel em propriedade familiar. *Pesquisa Agropecuária Tropical, 41*(1), 94-101. doi: 10.5216/pat.v41i1.10414

Silva, J. de S., Costa, R. S. D., Tomaz, F. L. D. S., Bezerra, A. E., & Mesquita, R. O. (2021). Mechanisms of tolerance to water deficit and physiological responses to rehydration in cowpea. *Revista Ciência Agronômica, 52*(3), e20207198. doi: 10.5935/1806-6690.20210034

Silva, J. S. de, Jr., Bastos, E. A., Cardoso, M. J., Andrade, A. S. de, Jr., & Ribeiro, V. Q. (2020). Production performance of BRS Tumucumaque cowpea under different plant densities and water regimes. *Revista Caatinga, 33*(1), 205-216. doi: 10.1590/1983-21252020v33n122rc

Silva, S., Silva, C. S. da, Souza, J. E., Paz Sousa, A. C. da, & Araújo, E. R. (2019). Uso econômico da água para o feijão caupi na região do sertão alagoano. *Revista Brasileira de Agrotecnologia, 9*(1), 7-13. doi: 10.18378/rebagro.v9i1.6452

Souza, P. J. O. P., Farias, V. D. D. S., Pinto, J. V., Nunes, H. G., Souza, E. B. D., & Fraisse, C. W. (2020). Yield gap in cowpea plants as function of water deficits during reproductive stage. *Revista Brasileira de Engenharia Agrícola e Ambiental, 24*(6), 372-378. doi: 10.1590/1807-1929/agriambi.v24n6p372-378

Tsunechiro, A., Duarte, A. P., & Okawa, H. (1995). Custo operacional da cultura de milho, por região e época, Estado de São Paulo. *Informações Econômicas, 25*(2), 53-60.

Vieira, G. H. S., Mantovani, E. C., Soares, A. A., Cunha, F. F. D., & Montes, D. R. P. (2011). Custo da irrigação do cafeeiro em diferentes tipos de equipamento e tamanhos de área. *Engenharia na Agricultura, 19*(1), 53-61. doi: 10.13083/reveng.v19i1.169

Vilas Boas, R. C., Pereira, G. M., Reis, R. P., Lima, J. A. D., Jr., & Consoni, R. (2011). Viabilidade econômica do uso do sistema de irrigação por gotejamento na cultura da cebola. *Ciência e Agrotecnologia, 35*(4), 781-788. doi: 10.1590/S1413-70542011000400018

Zamberlan, J. F., Robaina, A. D., Peiter, M. X., Ferraz, R. C., & Santos Nunes, M. D. (2011). Análise de benefício-custo levando-se em consideração os custos da água de irrigação para o arroz. *Revista Tecno-Lógica, 15*(2), 100-104. doi: 10.17058/tecnolog.v15i2.2074