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Articles

Estimation of the water footprint of beans grown under two irrigation variants and foliar applications of biostimulants

Estimación de la huella hídrica del frijol cultivado en dos variantes de riego y aplicaciones foliares de un bioestimulante

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ABSTRACT: The most food production comes from irrigated agriculture, which is therefore the largest consumer of water. As water scarcity increases, optimizing the efficiency of this resource is paramount for food production. The common bean (*Phaseolus vulgaris* L.) is the most important legume worldwide, especially in the tropics. Irrigation is essential to increase its yield, as it allows for the adequate supply of water at each stage of growth. On the other hand, water scarcity due to climate change is reducing water availability. The water footprint (WF) of a product is defined as the amount of water used throughout the entire production process. Particularly in agricultural products, the largest amount is used through irrigation during the growing stage; therefore, its quantification is important to raise public awareness of water use and the need to protect available water resources. The use of biostimulants in agriculture has increased, which is associated with their beneficial effects on plant growth, productivity, and protection. To estimate the water retention (WR) of beans grown under two irrigation conditions and with foliar applications of biostimulants, an experiment was conducted at INCA using the Tomeguín 93 cultivar. Irrigation and effective rainfall requirements were obtained using the CropWat 8 program. The results showed a beneficial effect of PectiMorf, both in increasing yield and in reducing total WR when the plants were grown with 50 % irrigation.

Key words: biostimulants, effective rainfall, evapotranspiration, yield.

RESUMEN: La mayor producción de alimentos proviene de la agricultura de regadío por ello, es el mayor consumidor de agua. A medida que la escasez de agua aumenta, optimizar la eficiencia de este recurso, es primordial para la producción de alimentos. El frijol (*Phaseolus vulgaris* L.) constituye la legumbre más importante a nivel mundial, especialmente en los trópicos. El riego es fundamental para incrementar su rendimiento, este permite el suministro de agua adecuado en cada fase del crecimiento. Por otra parte, la escasez de agua debido al cambio climático está reduciendo su disponibilidad. La huella hídrica (HH) de un producto se define como, la cantidad de agua empleada en todo el proceso productivo. Particularmente, en los productos del agro, la mayor cantidad se emplea mediante el riego en la etapa agrícola, por ello su cuantificación es importante para lograr mayor conciencia social de su uso y protección de los recursos hídricos disponibles. El uso de bioestimulantes en la agricultura ha aumentado, lo que se asocia a sus efectos beneficiosos en el crecimiento, productividad y protección de las plantas. Con el objetivo de estimar la HH del frijol cultivado en dos variantes de riego y aplicaciones foliares de un bioestimulante, se realizó un experimento en el INCA, con el cultivar Tomeguín 93. Los requerimientos de riego y precipitación efectiva (P. efec.) se obtuvieron mediante el programa CropWat 8. Los resultados manifestaron un efecto beneficioso del bioestimulante, tanto en el incremento del rendimiento, como en la reducción de la HH total cuando las plantas se cultivaron con el 50 % del riego.

Palabras clave: bioestimulantes, evapotranspiración, precipitación efectiva, rendimiento.

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INTRODUCTION

Water scarcity is a growing global concern, increasingly driven by population growth, urbanization, and the accelerating impacts of climate change (1,2). This progressive threat of freshwater scarcity and the persistent drought in recent years have activated research into different irrigation management strategies and water conservation to produce more crop per drop (3,4).

Water is essential for the survival of all organisms on Earth and is vital for maintaining food security, ecosystem stability, and socioeconomic prosperity (5). Therefore, balancing water availability and demand is crucial for achieving water sustainability. One of the challenges in maintaining this balance is that water availability is threatened by climate change and land-use changes (6).

Currently, water deficit is one of the most pressing global problems, and its importance will increase in the future. More than 40 % of global food production comes from irrigated agriculture; therefore, it is the largest water consumer, accounting for 70 % of all freshwater withdrawals. As water scarcity worsens globally, improving the efficiency of agricultural water resources becomes a primary goal for increasing food production (7).

Common bean (*Phaseolus vulgaris* L.) is the most important food legume worldwide, especially in the tropics, where it is the main source of protein, carbohydrates, and minerals, particularly iron and zinc (8). Irrigation is the best option for increasing crop yield, as it allows water supply in adequate amounts for each phase of the growth cycle (9). However, water scarcity resulting from climate change is reducing its availability for agriculture (4).

The agricultural sector is one of the most affected by global population growth. As food demand increases, water needs for agriculture rise, impacting the overall water demand in agriculture (10). Therefore, to mitigate these negative impacts, contemporary water conservation methods in agriculture increasingly employ water footprint assessments and virtual water analyses for agricultural products (11).

The water footprint measures the volume of water used or contaminated in the production of agricultural goods, reflecting the resources allocated to agriculture (12,13). It is generally divided into three components: blue, green, and grey water (10). Understanding these components and their correlations is crucial for effective water management and conservation strategies.

Agricultural water requirements can be calculated using the CropWat program, a Windows-based model designed to estimate crop water needs and irrigation requirements based on soil, climate, and crop data (14).

Deficit irrigation (DI) represents a solution in which water application is intentionally reduced below crop water requirements (CWR), resulting in higher water productivity (15). DI generates substantial water savings, accompanied by minimal yield reduction, which can be easily offset by superior product quality and cost savings associated with reduced water use (16).

In recent decades, the use of biostimulants in agriculture has increased significantly (17). The high demand for these compounds is associated with their beneficial effects on plant growth, productivity, and protection (18).

Biostimulants are of great importance for Cuba from both economic and environmental perspectives. Economically, they reduce costs related to agricultural input imports, since these biostimulants can be produced domestically using the positive contributions of these bioproducts to the country's food sovereignty and security is a reality that cannot be delayed, given the current economic context and the urgent need to produce food and reduce imports.

Based on the above, the objective of the study was to estimate the water footprint of common bean grown under two irrigation regimes and foliar applications of a biostimulant.

MATERIALS AND METHODS

The study was carried out in the central area of the National Institute of Agricultural Sciences (INCA), geographically located at 22°58′00″N and 82°09′00″W at an altitude of 130 meters above sea level. For this purpose, 12 concrete containers measuring 2.60 m in length by 0.60 m in width (1.56 m²) were planted in September 2024, containing leached Red Ferrallitic soil (19). In each container, 44 black bean plants (Phaseolus vulgaris L.) of the cultivar "Tomeguín 93" were sown, arranged in two rows with a separation of 0.40 m between rows and a spacing of 0.11 m between plants (28 plants per m²). This cultivar is characterized by an 80-day cycle and a potential yield of 2.9 $t \cdot ha^{-1}$ (according to the catalog of commercial grain varieties: Rice, bean, corn, soybean, sorghum. Grain Research Institute. 2021, Havana City, Cuba). Before sowing, a basal fertilization was carried out with an NPK (9-13-18) formula at a dose of 50 $kg \cdot ha^{-1}$, and another application with urea (46-0-0) at the same dose was performed 35 days after emergence (20).

Two irrigation treatments were used. In each of them, two applications of the biostimulant PectiMorf® were made at a rate of 150 $mg \cdot ha^{-1}$, the first at 20 days after sowing (DAS) and the second at the beginning of flowering (35 DAS). Additionally, two treatments without the product were included, resulting in the following four treatments:

- T C: with irrigation at 100 % of ETc (crop evapotranspiration under standard conditions) throughout the crop cycle. Designated as Control.
- T E: with irrigation at 50 % of ETc throughout the crop cycle. Designated as Stress.
- T C + P: with irrigation at 100 % of ETc + two foliar applications of the biostimulant.
- T E + P: with irrigation at 50 % of ETc + two foliar applications of the biostimulant.

The treatments were distributed according to a randomized block experimental design with three replications (three containers per treatment).

Irrigation was applied using an automated micro-sprinkler system. During the first week after sowing, all treatments received 100 % of ETc to ensure adequate germination and uniform initial growth; from that time onward, irrigation was applied according to the requirements of each treatment.

Soil moisture (%) was evaluated in all treatments at 25 and 40 days after sowing (five days after the foliar applications of the biostimulant), using a TDR probe (Time Domain Reflectometry) Field Scout TDR 100 System, Spectrum Technologies, Inc. Thirty measurements were taken (10 in each container) at a depth of 20 cm.

Yield and its components were evaluated on 10 randomly harvested plants per container (30 plants per treatment). The following parameters were measured: number of pods per plant, number of grains per pod, fresh mass, and 100-grain mass. In addition, the total yield of each container ($kg \cdot m^{-2}$) was evaluated. To estimate yield in $kg \cdot ha^{-1}$, yield in $kg \cdot m^{-2}$ was multiplied by 10,000 = $kg \cdot ha^{-1}$.

Data processing and mean comparison were performed using the statistical software IBM SPSS Statistics 19.

The estimation of the blue, green, grey, and total water footprint of the crop was carried out following the methodology proposed by (21).

For the calculation of the blue and green footprints, the CROPWAT 8.0 model was used. This model allows the determination of potential and actual evapotranspiration, estimation of irrigation needs for one or several crops in a given area, and facilitates irrigation planning. According to (14), CropWat offers advantages for calculating crop water requirements and scheduling irrigation. It also facilitates the development of irrigation calendars for different management scenarios and provides calculations for water supply schemes adapted to various cropping patterns. Furthermore, CropWat can be used to evaluate irrigation practices and plant performance in relation to water requirements and is based on the methodologies described in FAO Irrigation and Drainage Paper bulletins 24, 33, and 56.

Irrigation consisted of replenishing ETc three times per week (Monday, Wednesday, and Friday). Reference evapotranspiration ETo (mm), ETc (mm), and crop water requirements (CWR) were obtained using the aforementioned program, which was updated with a 33-year historical series of meteorological data (1990-2023) from the Tapaste meteorological station, belonging to the National Institute of Meteorology (INSMET), located approximately 500 m from the experimental site. For the calculation of ETo and ETc, the monthly mean values of all variables involved in the calculation were used. The crop coefficients (Kc) used were: Kc initial = 0.15, Kc mid = 1.10, and Kc end = 0.35, proposed for the region by FAO.

In CROPWAT 8.0, the CWR option was used, defining four of the five modules that make up the model, which yielded the following variables: ETc and effective precipitation (P ef).

RESULTS AND DISCUSSION

Table 1 shows soil moisture variations by treatment and evaluation date. At 25 DAS, treatments T C and T C+P had soil moisture near 100 % of field capacity (FC), while at 40 DAS, T C+P moisture dropped to approximately 90 % of FC. At 25 DAS, T E+P showed higher moisture (80 % of FC) than T E (70 % of FC). At 40 DAS, moisture values were 60 and 63 % of FC for T E and T E+P, respectively.

This behavior shows the effect of the irrigation treatments on soil moisture differences, as well as a slight beneficial effect of the foliar applications of the biostimulant on plant water economy when plants are under soil water deficit conditions.

The results of the effect of the different irrigation treatments and foliar applications of the biostimulant on plant yield and its components are presented in Table 2.

In general, the highest values of the different variables involved in yield corresponded to plants from treatments T C and T C+P, with differences between them in number of pods, grains per plant, and yield in grams per square meter.

Table 1. Soil moisture percentages at 25 and 40 DAS in the different irrigation treatments with and without biostimulant applications

Tratamientos / DAS	T C%	T C +P%	T E%	T E+P%	E.s. X
25	38.66 a	34.14 b	25.18 d	29.30 c	0.762 *
40	34.58 a	31.69 a	20.44 c	27. 61 b	0.661 *
Mean	36.62	32.91	22.81	28.45	

T C: irrigation at 100 % of ETc (Control). T C+P: Control + foliar applications. T E: irrigation at 50 % of ETc (Stress). T E+P: Stress + foliar applications. (Standard error of the mean. α = 0.05)

Table 2. Yield components of common bean plants cultivated under two irrigation treatments and biostimulant foliar applications

Treatments / Variables	T C	T E	T C+P	T E + P	SE
Number of pods per plant	7. 7 a	4. 7 c	6. 4 b	5. 9 b	0.171 *
Number of grains per pod	4. 6 a	3. 4 b	3. 7 b	4. 2 a	0.112 *
Grains per plant	33. 6 a	15. 6 c	28. 3 b	24. 4 b	0.629 *
100-grain mass	18. 45	17. 48	18. 49	17. 94	0.636 ns
Yield in $g \cdot m^{-2}$	173. 6	76. 4	146.4	122.5	estimated
Yield in $kg \cdot ha^{-1}$	1736	764	1464	1225	estimated

T C: irrigation at 100 % of ETc (Control), T C+P: Control + foliar applications, T E: irrigation at 50 % of ETc (Stress), T E+P: Stress + foliar applications. (Standard error of the mean. α = 0.05)

It is worth noting that, under this irrigation treatment, the foliar applications of the biostimulant did not show a clear beneficial effect on the increase in the magnitude of these variables. However, when comparing these values between T E+P and T E plants, a considerable effect of the biostimulant was observed, with increases in all yield-related variables.

Undoubtedly, the 50 % reduction in applied irrigation water caused a considerable reduction in yield in $g \cdot m^{-2}$ and $kg \cdot ha^{-1}$ (56 %) between T C and T E plants and (16 %) between T C+P and T E+P plants, demonstrating the beneficial effect of the biostimulant applications. It should be noted that the estimated yield values for both T C and T C+P plants are within the range of yields (22) working with the same species under three planting dates (September, November, and January) and with the black-grain cultivars "Cuba Cueto 25 N" (1695.8 $kg \cdot ha^{-1}$) and "ICA PIJAO" (1550.9 $kg \cdot ha^{-1}$). They also noted that the highest yields were obtained in September planting, associated with higher rainfall and temperatures, largely coinciding with (23), who stated that the number and weight of grains per pod, and more specifically the number of pods per plant, are the characteristics most affected in common bean under soil water deficit conditions.

Research carried out by (24) with the black bean cultivar "Triunfo 70", saving 60 % of irrigation water, found negative effects on the physiological response of plants to water deficiency. However, regarding yield, only a decrease in the number of pods per plant was found, which largely agrees with (25), who, working with 100 specimens of *Vicia faba*, stated that moderate water stress negatively affects the number of pods per plant without reducing grain size or the number of grains per pod.

Studies in Iran examined the effect of four irrigation treatments (25, 50, 75, and 100 % of crop water requirements (26), CWR) on *Vigna radiata* and three foliar applications (0, 10, and 20 millimoles (mM) of ascorbic acid). They found that the highest yield (1228 $kg \cdot ha^{-1}$) corresponded to the 75 % CWR treatment with 20 mM ascorbic acid.

The water footprint measures the volume of water used or contaminated in the production of agricultural products, reflecting the resources allocated to agriculture (12-13). It is generally divided into three components: blue, green, and grey water (11). Understanding these components and their correlations is crucial for effective water management and conservation strategies.

The accumulated values of green ET and blue ET over the 80-day crop cycle (Table 3) indicate that, regardless of the treatment, the contribution of irrigation (blue ET) to crop evapotranspiration was always greater.

The grey component of the water footprint was calculated according to the proposed methodology and using the following expression:

$$WF_{gray}\left(m^3\,t^{-1}\right) = \frac{\frac{N_{excess}}{(C_{max} - \; C_{nat})}\left(m^3 \;\; ha^{-1}\right)}{production \;\; \left(t \;\; ha^{-1}\right)}$$

Where N excess ($kg \cdot ha^{-1}$) represents the amount of nitrogen that escapes from the crop rhizosphere. A value of 0.10 was assumed, in accordance with various regulations and directives that agree on this value for nitrogen (e.g., EU Nitrates Directive, 91/676/EEC; Resolução CONAMA nº 357, of March 17, 2005*). C max represents the maximum allowable N concentration in the receiving water body, with a value of 50 mg $NO_3 \cdot L^{-1}$ according to the Salvadoran Mandatory Standard for Wastewater Discharged into a Receiving Body, CONACYT NSO:13.49.01:09, 2009 (27). C nat is the background N concentration in the receiving water body prior to the polluting activity, generally considered negligible in many studies (=0).

The grey water footprint (WF grey) was calculated as follows:

$$\begin{aligned} WF \;\; grey \;\; &= \;\; 27.5 \;\; kg \cdot ha^{\cdot 1} \;\; \times \;\; 0.10 \\ &= \;\; 2.75 \;\; kg \cdot ha^{\cdot 1} \;\; / \;\; 50 \;\; mg \cdot L^{\cdot 1} \\ &= \;\; 2.75 \;\; / \;\; 0.00005 \\ &= \;\; 55{,}000 \;\; L \cdot ha^{\cdot 1} \;\; 55{,}000 \;\; L \cdot ha^{\cdot 1} \;\; / \;\; (1736 - 764 - 1464 - 1226) \\ &= \;\; (31.7 - 72.0 - 37.5 - 44.9) \;\; L \cdot kg^{\cdot 1} \\ &= \;\; (0.02 - 0.072 - 0.037 - 0.045) \;\; m^3 \cdot kg^{\cdot 1} \end{aligned}$$

The values of green, blue, grey, and total water footprint are presented in Table 4. It was found that the total WF values for plants under treatments T C and T C+P were very similar, differing by only 0.213 $m^3 \cdot kg^{-1}$. This indicates that the foliar applications of PectiMorf had a very slight effect on reducing total WF when plants were grown under adequate water supply conditions, a trend consistent with the yield results.

On the other hand, the difference between plants from treatments T E and T E+P was 1.64 $m^3 \cdot kg^{-1}$, demonstrating the beneficial effect of these applications in reducing total WF when plants were under lower water supply conditions.

It is worth noting that the lowest total WF values corresponded to plants that received the biostimulant applications, regardless of the irrigation treatment, even though they showed the lowest yields. Also, in this case, the greatest contribution to total WF came from irrigation.

Table 3. Accumulated values of the contribution of rainfall to evapotranspiration (green ET) and of irrigation (blue ET) by treatment

Treatment / Variables	T C	T E	T C+P	T E + P
Green ET (mm)	134.4	134.4	134.4	134.4
	26 %	**41 %**	**26 %**	**41 %**
Blue ET (mm)	384.9	192.4	384.9	192.4
	74 %	**59 %**	**74 %**	**59 %**

T C: irrigation at 100 % of ETc (Control), T C+P: Control + foliar applications, T E: irrigation at 50 % of ETc (Stress), T E+P: Stress + foliar applications

Table 4. Water footprint of common bean plants grown under two irrigation regimes and foliar applications of PectiMorf

Treatment / Variables	T C	T E	T C+P	T E+ P
Green WF (m^3 Kg^{-1})	0.77	1.76	0.92	1.10
Blue WF (m^3 Kg^{-1})	2.22	2.52	2.63	1.57
Gray WF (m^3 Kg^{-1})	0.02	0.072	0.037	0.045
Total WF (m^3 Kg^{-1})	3.80	4.352	3.587	2.715

T C: irrigation at 100 % of ETc (Control), T C+P: Control + foliar applications, T E: irrigation at 50 % of ETc (Stress), T E+P: Stress + foliar applications

In studies carried out on faba bean (*Vicia faba*) (28), two irrigation treatments (25 and 50 % of management allowable depletion, MAD) were tested, which influence the distribution of green and blue WF, along with two planting patterns (single row L1 and double row L2). It was found that the combination of frequent irrigation (25 % MAD) and a denser plant cover (L2) optimized transpiration and reduced evaporation losses, contributing to a lower water footprint (~0.638 $m^3 \cdot kg^{-1}$). Additionally, it was noted that a lower water footprint not only indicates greater water productivity but also contributes to more sustainable and climate-resilient agricultural practices in water-scarce regions.

CONCLUSIONS

- When analyzing the effect of the two irrigation regimes studied and the foliar applications of the biostimulant on the common bean crop, it was demonstrated that under lower water supply conditions, the foliar applications of the product had a beneficial effect on yield increase, with higher values for number of pods per plant, number of grains per pod, and grains per plant, variables that defined the higher yield.
- Furthermore, this beneficial effect was also evident in the reduction of total water footprint. It was also found that the greatest contribution to the total water footprint came from irrigation. Further research is suggested on the agricultural application of this type of product, given its importance for crop adaptation or tolerance to climate change, as well as for water and energy savings.

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