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Efficiency assessment of rainwater collecting in greenhouses

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Abstract: Rainwater harvesting is an effective alternative for soil and water conservation. Achieving sustainable management of diverse water sources is a global challenge, requiring effective local solutions. Applying rainwater harvesting methods ensures the reliability of agricultural production and mitigates the effects of extreme events. The study evaluated the efficiency of rainwater harvesting from the roofs of three farm buildings under different climatic conditions, using benefit indicators for environmental, socioeconomic, and productive protection. The results demonstrated that the harvested rainwater protects the soil and prevents losses due to potential sheet erosion in the surrounding areas of the houses studied, ranging from 0.06 to 5.00 t ha^{-1} yr^{-1}. Furthermore, good-quality water is guaranteed for domestic use and human consumption to a total of 202 people for 30 days during the dry season, with water collected from only one 540 m^2 farm building. It was also demonstrated that in each region it will be possible to design different types of cisterns and tanks with a capacity to store more than 480 m^3, which satisfies the water needs of important crops such as: tomato, pepper and cucumber.

Key words: water use; indicators; potential erosion

1 Introduction

Water is essential for life, and its scarcity affects a region's development prospects. Without available water, the potential for economic progress and social well-being are compromised. On the other hand, excess water can also cause severe damage to production and life (crop losses, soil depletion due to leaching and erosion, risks of landslides, avalanches, and floods, among others). An alternative with great potential is rainwater harvesting, since its collection only requires a collection system. This has certain advantages, such as energy savings, since it avoids the entire extraction process, distribution system, and pumping for transport to the supply area. The treatment required to ensure adequate quality for human consumption is relatively inexpensive. A disadvantage is that water availability is limited to the high rainfall seasons and varies for each region of the country, and also depends on the size of the catchment area and the size of the building's cistern if already implemented (Rojas-Valencia et al., 2012).

FAO (2013) notes that, under the perspective of global warming, the problem of water scarcity tends to worsen in regions where water shortages already exist, either due to the tendency toward reduced precipitation levels or increased evaporation and transpiration rates. Thus, the problem in the region could spread and become more acute, reaching currently sub-humid and humid areas.

Rainwater harvesting is a technology that creates impermeable roofs and areas to capture rainwater, then channel it to storage locations (reservoirs, cisterns) and ultimately to a use (for human, agricultural, or livestock purposes). Rainwater harvesting is used intensively in many areas of the planet, emerging since ancient times as a result of water demand. Herrera (2010)[1].

Rainwater harvesting can be achieved through both roof flows and intermittent or ephemeral surface runoff. It can also be beneficially utilized in arid and semi-arid regions, as well as in sub-humid regions, where growing competition between sectors for water resources is increasing the use of alternative techniques, which help reduce the effects of rainfall fluctuations on crop production and water availability. Rainwater planning and management can also reduce risks, prevent health problems, and mitigate disasters (Pacheco, 2008).

In Cuba, the current historical average precipitation is 1,335 mm; however, it has an uneven seasonal and geographical distribution with variable behavior, resulting in cyclical trends where extreme events associated with rain, such as heavy rainfall and droughts, recur.

Rainwater harvesting and storing it in cisterns is still a new concept for many people. However, this practice will be key in the future to ensure the supply of good-quality water to urban and rural populations in arid areas (Hieronimi, 2006).

The collection of rainwater through the diversion of the first few millimeters provides good quality water at a low cost in a tank of suitable size for people with few resources (Doyle, 2010)[2].

The study presented aims to evaluate the efficiency of rainwater harvesting from the roofs of three houses under different edaphoclimatic conditions, through indicators of benefit, environmental protection, socioeconomic factors, and productivity.

2 Methods

For the study, three cultivation houses of 540 m^2 each were selected, located in Camalote, Camagüey "La Pupa" Bayamo and in Ceballos Ciego de Ávila.

In each of the regions, station selection criteria were based on proximity to the study area and completeness of the series. Rainfall was studied with a 30-year lag time at the following stations: La Bayamesa (Lat 20.387–Long 76.623); Camalote (Lat 21.386–Long 77.15); and Ceballos (20.38–Long 76.723) (Figure 1).

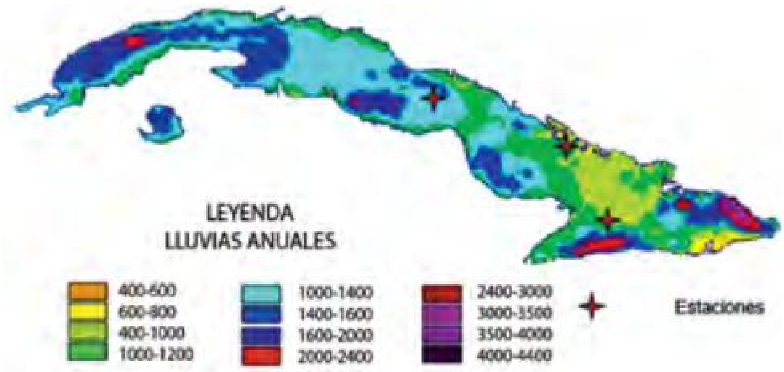


Figure 1. Location of Meteorological Stations (INRH 2005)[3]

The rainfall design was determined through statistical analysis of the probability of the selected sample. A graphical method was used to determine the probability or frequency of annual occurrence of seasonal rainfall according to FAO (2013).

To design the tanks that would store the captured water, the possible volume was determined; according to (Palacio, 2010).

$$Ai = \frac{Ppi * Ce * Ac}{1000} \quad (1)$$

Where:

Ppi: average monthly precipitation (L/m^2);

Ce: Runoff coefficient;

Ac: Catchment area (m^2);

Ai: Supply corresponding to month "i" (m^3).

To understand the type of soil, the relief, and other points of interest in each of the studied locations, the map created by the LADA project (2010)[4] at a scale of 1:250,000 was analyzed.

The site located in Camalote, Camagüey presents Brown soils with carbonates supported on transported materials of calcareous origin with a sialitic evolution in a medium rich in calcium, they are located on flat topography with clayey minerals of type 1:1 (kaolinite) and 1:2 montmorillonite, they are moderately deep and little eroded soils.

In "La Pupa" Bayamo there is a poorly differentiated Fluvisol with a high degree of structuring, with an apparent density greater than 1.20 g cm^{-3} and infiltration less than 10 mm $hour^{-1}$.

In Ceballo, Ciego de Ávila, the soils are red Ferralitic, throughout their profile, clayey with an effective depth of 45 cm presenting good internal and superficial drainage, little eroded and with a certain degree of gravel. Among the limiting factors we can mention the effective depth, the excess of stones and the risks of erosion.

To analyze the benefits of rainwater harvesting from the roofs of farm buildings and the efficient use of collected rainwater, three indicators were selected to define efficiency:

- Protection and maintenance value: As a mechanism that helps conservation, reducing the risks of water erosion.

- Socioeconomic Value: Assesses the impact of captured and stored water resources on social well-being.

- Productive Value: For productive use, it could compensate for water needs during the critical period of crops with supplementary irrigation and for consumption by domestic animals.

To calculate qualitative erosion risk values, we used the modified universal soil loss equation (Wischmeier and Smith, 1958; Taylor, 1970), an empirical, parametric model that has been tested and validated under various soil, climate, and management conditions and is based on the main factors affecting soil erosion According to Bonilla (2010)[5].

$$\mathbf{A = R * K * L * S * C * P} \quad (2)$$

Where:

A = average annual soil loss per unit area (t $ha^{-1} \cdot year^{-1}$);

R = rainfall erosivity factor (kJ mm m^{-2} $hour^{-1}$ $year^{-1}$);

K = soil erodibility factor (t m^2 hour·ha^{-1} kJ^{-1} mm^{-1});

L = slope length factor;

S = slope (%);

C = vegetation cover factor (dimensionless and comes tabulated, according to the characteristics of the vegetation);

P = crop conservation practices factor

"Potential erosion" is estimated with equation 2, but eliminating the "C and P" factors.

The topographic factor Ls is obtained through the expression developed by Bertoni (1959) which can be read using a nomogram according to (Sámano, 2009)[6].

$$Ls = 0.00984 * L^{0.63} * S^{1.18} \quad (3)$$

Where:

Ls - Topographic factor;

L - Slope length in meters, expressing the distance from the point where the raindrop falls to the point where the slope decreases and deposition begins, or to a defined watercourse;

S - Land slope in percentage.

The Erosivity Factor due to rainfall "R" in [MJ ha^{-1} mm h^{-1}], was determined using the formula of Lombardi and Moldenhauer (1980), taken from Sámano (2009).

$$R = 6.866 * (\frac{p^2}{Pa})^{0.85} \quad (4)$$

Where:

R- Average annual erosivity index;

p- Average monthly precipitation;

Pa - Average annual precipitation.

The soil erodibility factor "K" represents the susceptibility of the soil to erosive action and will depend on the physical characteristics of the soils: texture, permeability, filtration capacity, structure, granulometry, organic matter content, etc. It is expressed in [t ha^{-1} MJ·ha^{-1} mm·h^{-1}]. This factor was determined based on the predominant soil and the texture, using the methodology proposed by FAO (1980) which includes the soil unit according to the FAO/UNESCO classification (1980) and the surface textural class of the soil, applying the criteria of the soil classification of the Soil Institute (1999).

The Socioeconomic Value is studied based on the assumed allocation per person. The amount of water needed to meet the needs of the beneficiary family for each month is calculated. The calculation is made using the following formula (Palacio 2010):

$$Di = \frac{Nu * Nd.Dot}{1000} \quad (5)$$

Where:

Nu - number of users benefiting from the system;

Nd - number of days in the month analyzed;

Dot - allocation (L $person^{-1}$ day^{-1});

Di - monthly demand (m^3)

Productive Value: Taking as an example the crops: tomato, cucumber and pepper in protected conditions of table 17 of the *Manual for the Protected Production of Vegetables* (MINAGRI, 2007), the water consumption by plants in a life cycle is obtained.

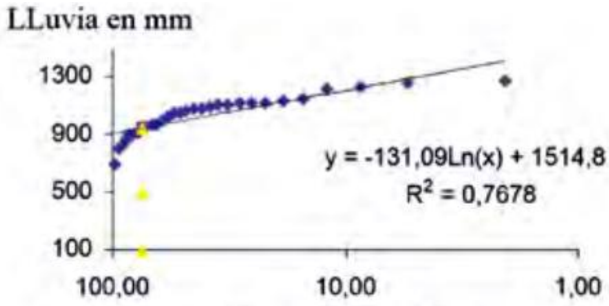
In all three cases, an A-12 grow house of 540 m^2 is considered, these have a density of 1,200 plants, with an irrigation interval every two days, medium to heavy soil with a total of 1,760 emitters with an effective expenditure of 2 L h^{-1} each.

3 Result and discussion

When evaluating the potential for rainwater harvesting in the selected regions, the roofs of the farm buildings are used as a catchment area. All roofs in farm buildings can capture good-quality water, and the investment is profitable because once erected, the structure lasts 40 or 50 years.

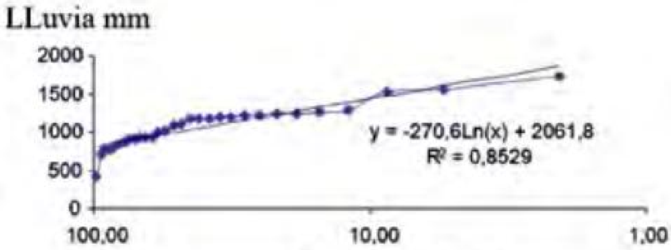
The series taken for the rainfall studies at the chosen stations with a delay time of 30 years, according to the statistical analysis are reliable, taking into account what was proposed by Chavarri (2006); which indicates that the statistical parameter Coefficient of variation (Cv) can be used quantitatively to show that values less than 0.20 and up to 0.25 of this, indicate for most purposes an acceptable length of the series to obtain reliable estimates and moderate variability.

From the probability diagrams, Figures 2, 3 and 4, the design rainfall was determined for a 67% exceedance level. That is, on average, 67% of the time (2 out of 3 years), the annual rainfall will equal or exceed 967.3 mm in Bayamo, 924 mm in Camalote and 1,125 mm in Ceballo. That is, in two years out of three the annual rainfall will be this high, and one year out of 3 the rainfall corresponding to the 33% will be 1,056.44 mm, 1,115.6 mm and 1,311 mm respectively in Bayamo, Camalote and Ceballo. Taking into account the runoff from the materials of the houses, the efficiency in the collection of rainwater from the roofs for this probability level is 0.603. This shows us that it is feasible to carry out storage and conduction works for the rainwater collected from the roofs.



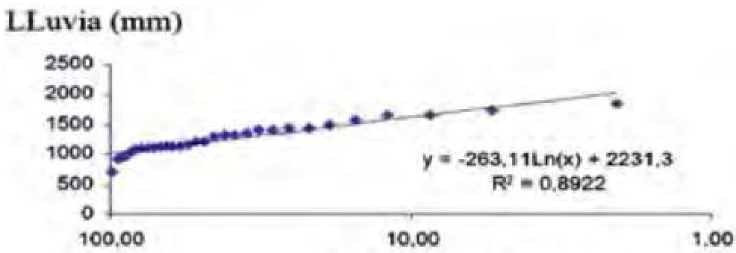
Probability P(%)

Figure 2. Probability diagram with regression line of annual totals Bayamo



Probability P(%)

Figure 3. Probability diagram with regression line of the annual totals Camalote



Probability P(%)

Figure 4. Probability diagram with regression line of Ceballo's annual totals

Therefore, the possible volumes of water to be collected by each house are determined, considering the runoff coefficient generated by the material of their roofs, which according to CIDECALLI-CP (2011) is 0.9 given their origin and the collection area of a single cultivation house; as can be seen in Figures 5, 6 and 7, the Bayamo Module will allow the collection of approximately an accumulated volume of 488.7 m^3 of water, Camalote 524.70 m^3 and Ceballo 600.72 m^3.

Based on the potential volumes of water to be collected and stored in cisterns designed for each house, it was possible to evaluate the benefits of their use.

The study of laminar erosion through the Universal Soil Loss Equation RUSLE (2), shows in an indicative way, the possible negative effects of rain in each of the regions if these waters are not captured.

Each factor in the equation was evaluated taking into account the peculiarities of each region, and eliminating the factors "C (vegetation cover factor) and P (crop conservation practices factor)" to estimate the erosion behavior with unprotected soils and without taking into account any conservation practices.

When all factors of the Universal Soil Loss Equation (RUSLE) are considered, current water erosion is said to have been calculated. However, when factors C and P are not included, potential water erosion has been calculated, that is, an estimate of how much soil would be lost if there were no vegetation cover and no conservation practices were carried out. (Itzel 2013)

The study of erodibility "K" defined by soil type (Table 1) is not significant in the study areas, with the highest values found in the Pardossialitic soils of Camalote; this coincides with the results of Marrero et al. in 2006 for this soil type; however, this factor is not a determining factor.

Table 1. Values acquired by erodibility (K)

Module	Soil Type	K
Camalote	Pardo Sialítico (B)	0.26
Ceballo	Ferralítico (A)	0.21
Bayamo	Fluvisol (C)	0.125

The Ls factor (3), defined by the topography of the region, presents very low values as can be seen in Table 2, determined by the existing slopes in the study areas which are less than 1%.

Table 2. Topographic factor (Ls)

Module	Ls
Bayamesa	0.1
Ceballo	0.11
The Flowers (Camalote)	0.13

However, the erosivity index that depends on rainfall "R" (4), as can be seen in Figure 6, indicates that rainfall determines soil loss in the three regions, taking into account that the houses are located in areas with flat topography and that from the edaphological point of view, tolerable or acceptable soil loss, without significantly affecting productivity, varies from 0.4 to 1.8 t ha^{-1} $year^{-1}$ (FAO, 1980).

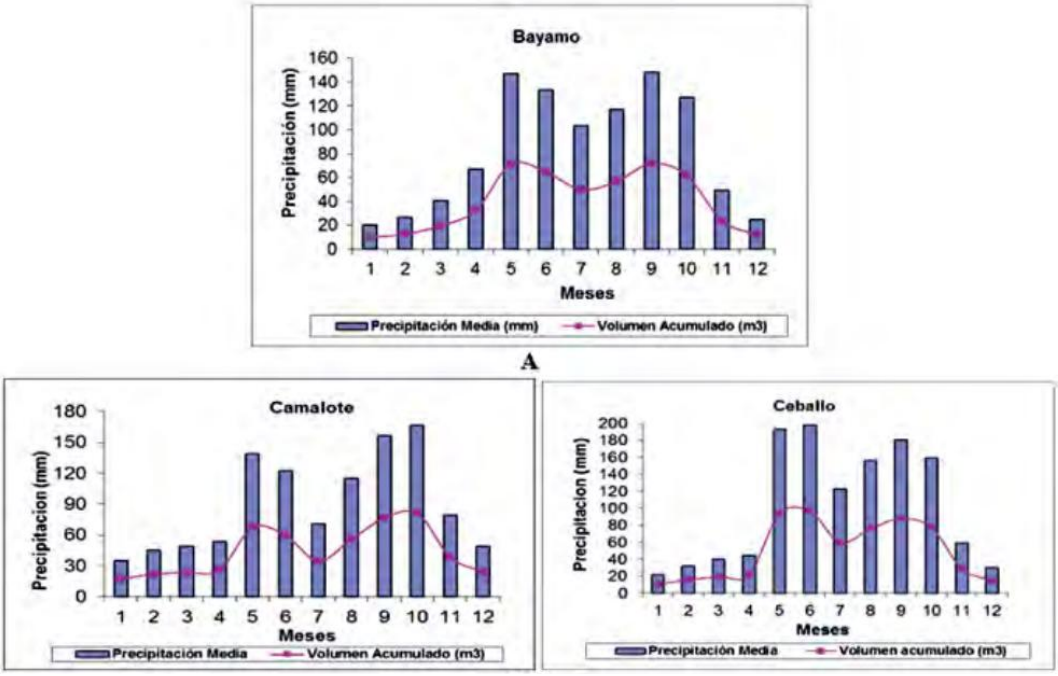


Figure 5. Average precipitation and accumulated volume in: A-Bayamo, B- Camalote, C- Ceballo

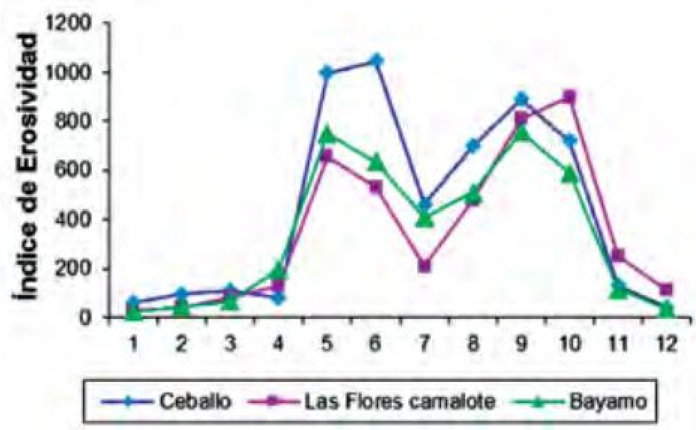


Figure 6. Erosivity index

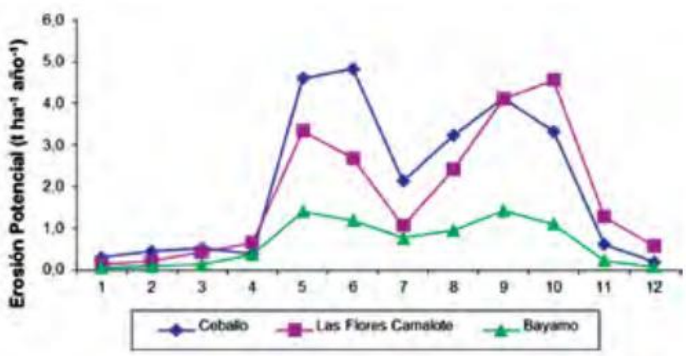


Figure 7. Potential erosion

As can be seen in Figure 7, which shows the losses due to potential erosion, the module located in Bayamo is located in this environment, while Camalote and Ceballo present values greater than 2 t ha^{-1} $year^{-1}$, a logical situation since the average rainfall in these regions is higher than in Bayamo (Figure 8); therefore, it can be stated that in both cases, rainfall is the main cause of losses due to sheet erosion, an action that is complemented by surface runoff. Therefore, storing the captured water reduces the risks of erosion and generates environmental and social benefits.

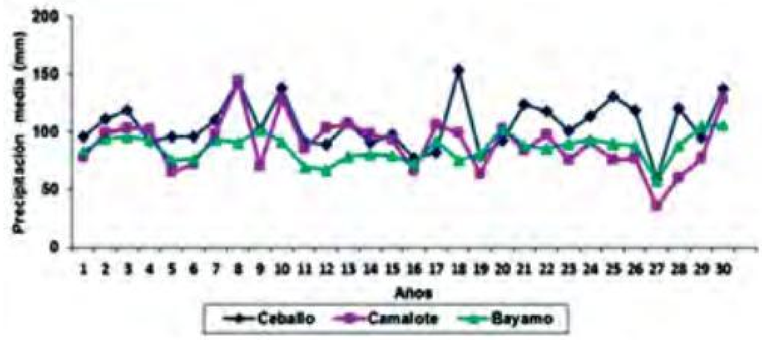


Figure 8. Average precipitation over a 30-year period

Another important indicator studied for the three regions, which allowed the socioeconomic value of rainwater harvesting to be assessed, was the study of the quantity of liters of water per person per day available in areas for human consumption, where a provision was applied in relation to needs, recommended by the WHO of 100 L $person^{-1}$ d^{-1} according to García (2008) (equation 5). This represents a solution for supplying populations with both quantity and quality.

The results in Table 3 show that a total of 168 people in Camalote, 158 in Bayamo, and 202 in Ceballos would benefit from the water collected by just one 540 m^2 cultivation house over a 30-day dry season.

Table 3. Number of users who benefit from the use of collected water

	Camalote		Ceballos		Bayamo	
Months	Volume (m^3)	Users who benefit	Volume (m^3)	Users who benefit	Volume (m^3)	Users who benefit
January	17.10	5	10.54	3	10.11	3
February	21.79	8	16.03	6	12.93	4
March	23.61	7	19.98	6	19.71	6
April	25.82	8	22.29	7	32.70	11
May	67.41	21	96.81	31	71.44	23
June	59.37	20	99.56	33	64.80	21
July	34.47	11	61.57	20	50.13	16
August	55.79	18	78.58	25	56.84	18
September	76.25	25	90.64	30	71.93	24
October	81.02	26	79.93	26	61.97	20
November	38.40	12	29.50	10	24.12	8
December	23.66	7	14.58	5	11.99	4
Annual	524.70	168	620.32	202.00	488.66	158

To assess the productive indicator, the water consumption of tomatoes, peppers and cucumbers was taken into account, as recommended by the *Manual for the Protected Production of Vegetables* in 2006 for medium and heavy soils, which, as can be seen in Table 4, can satisfy the water needs of a complete cycle, based on the volume of water collected in a cultivation house.

Table 4. Water requirements of crops in a life cycle

Crop	Phases	$L \cdot plants^{-1}$	Interval in days	$L \cdot d^{-1}$	Liters
	1	0.5	2	600	1,200
	2	0.7	2	840	1,680
Tomato	3	1	2	1,200	2,400
	4	1.4	2	1,680	3,360
	5	1	2	1,200	2,400
Total Tomato					11,040
Pepper	1	0,5	2	600	1,200
	2	0,8	2	960	1,920
	3	1,5	2	1,800	3,600
	4	1,2	2	1,440	2,880
Total Pepper					9,600
cucumbers	1	0,6	2	720	1,440
	2	0,8	2	960	1,920
	3	1,2	2	1,440	2,880
	4	1,5	2	1,800	3,600
	5	1,2	2	1,440	2,880
Total Cucumber					12,720
Total					33,360

Considering that the total water demand for the three crops averages 33,360 liters, the accumulated volume at the Bayamo Grow House, where rainfall is lower than that of Ceballos and Camalote, exceeds 480 m^3 annually. Therefore, the collected and stored water guarantees the production of a full harvest of cucumber, tomato, and pepper, meeting the water needs of these crops throughout their life cycle under protected conditions.

Each of the indicators studied shows that rainwater harvesting from the roofs of farm buildings guarantees environmental goods and services through the provision of water and food and soil protection.

4 Conclusion

• The annual rainfall at a level of 67% in the three regions guarantees a collection efficiency of 0.603, making it feasible to carry out storage and conduction works for rainwater collected from roofs.

• The potential sheet erosion indicator evaluated indicates that rainwater harvesting prevents losses from potential sheet erosion in the vicinity of the houses studied, ranging from 0.06 to 5 t ha^{-1} yr^{-1}.

• Rainwater harvesting from the roof of a 540 m^2 grow house guarantees high-quality water for domestic and human consumption, on average, for a total of 176 people during the 30-day dry season.

• The captured and stored water ensures the production of a cucumber, tomato, and pepper crop, meeting the water needs of these crops throughout their life cycle under protected conditions.

• Rainwater harvesting from the roofs of farms guarantees environmental goods and services through the provision of water, food, and soil protection.

Conflicts of interest

The author declares no conflicts of interest regarding the publication of this paper.

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