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Water and Carbon Footprints of Biomass Production Assets: Drip and Center Pivot Irrigation Systems

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Abstract: Studies on the environmental footprints of agricultural production have strong links with 4 out of the 17 Sustainable Development Goals (SDG) established by the United Nations. Irrigation systems are essential tools for increasing agricultural yields, particularly in arid regions. However, the production and assembly of these systems can have significant environmental impacts, including excessive water consumption and greenhouse gas emissions. Although studies have approached biomass production, few of them have provided data about asset depreciation, such as irrigation systems, machinery, etc. Trying to fill this gap, this study aimed at determining the water and carbon footprints of two commonly used irrigation systems: center pivot and drip. Several variables, including the irrigated area, pump power, filter type, system flow, and pipe length, were analyzed to determine the carbon and water footprints of each component of the irrigation systems. The results reveal that the materials used for pipes and filters had the most significant impact on the water and carbon footprints, with galvanized steel pipes and sand filters having the highest footprints. Additionally, the irrigated area affected the center pivot and drip systems differently, with the depreciation of the irrigation systems being a significant variable for both water and carbon footprints. These results can support the development of sustainable irrigation practices that reduce environmental impacts while enhancing agricultural yields. Decision-makers can use this information to establish a life-cycle database and evaluate the impact of irrigation systems on water and carbon footprints.

Keywords: sustainability; life-cycle assessment; environmental analyses; environmental impacts; environmental footprints; agricultural engineering

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1. Introduction

Studies on the environmental footprint of agricultural production have strong links with 4 of the 17 Sustainable Development Goals (SDG) established by the United Nations [1], for instance, SDG 2—Zero hunger, SDG 9—Industry, innovation and infrastructure, SDG 12—Responsible consumption and production; and SDG 13—Climate action. SDG 2 promotes sustainable agriculture and supports equal access to farming technologies. There is awareness regarding investment and research in infrastructure and technology to improve agricultural yields. SDG 9 regards technological progress, which aims to search for long-term solutions to sustainability challenges, such as promoting human labor insertion and energy efficiency. Based on scientific research and innovation, sustainable industries are vital to easing the path to sustainable development. SDG 12 aims at economic growth and sustainable development, for which it is desirable to reduce the ecological footprint through modifying production systems and consumption standards. Agriculture is the main water consumer globally, and irrigation is responsible for 70% of freshwater for human use. SDG 13 requires actions to integrate disaster-risk measures, the sustainable use of natural resources, and human security as part of countries' development strategies [1].

Agricultural production is constantly subject to the rainfall regime and the levels of precipitation in production areas. To minimize the negative effect of possible drought on yields and to increase the profitability of agricultural activity, farmers have increasingly invested in irrigation systems as a way of assuring water supply for crops. It is estimated that worldwide, 275 million hectares are dedicated to irrigated crops, which corresponds to 45% of total food production [2–4]. The world leaders in irrigation are China and India, with around 70 million hectares (Mha) each. Brazil stands currently in the sixth position, with 8.2 million hectares.

The predominant irrigation methods are localized (micro-sprinkler or drip), superficial (furrows or flood), sprinkler by center pivots, and sprinkler by other systems. Among these systems, [5] highlighted that especially in arid or semi-arid regions, sprinkler, micro-spray, and drip irrigation systems are more efficient and have advantages for achieving sustainability and developing rural economies [6]. However, although some irrigation systems are more efficient, it is highlighted that the assembling of irrigation systems requires materials, equipment, and energy, which affects water consumption and greenhouse gas emissions [7]. Thus, although irrigation systems promote higher yields, they also increase the demand for energy, the use of water, and other inputs.

During the Green Revolution (1960s), agricultural inputs were widely applied to achieve higher yields. However, in the following decade (1970s), sustainability emerged as a critical issue, emphasizing the efficient use of resources and the avoidance of negative environmental impacts. While the use of inputs has increased production, it has also diminished sustainability by threatening ecosystem stability [8] through potential water pollution and greenhouse gas emissions [9].

Since then, the carbon footprint has become increasingly important in production systems, and it has been studied in recent decades to manage greenhouse gas emissions, contributing to the mitigation of climate change. Carbon footprint is a term usually applied to approach the amount of carbon dioxide and other greenhouse gases generated by an organization, event, or product. In the last few years, due to climate change, it became a popular and widely used term, in strong demand by society [10,11].

As a proposition inferred by the method in [12], the appropriation of freshwater resources along the productive chain is defined as the water footprint, and among the different types of water footprint, the blue water footprint regards the volume of surface and underground water used in the production of one good. For agricultural machinery, the water and carbon footprints have already been assessed [13]. However, there is little information about the water footprint related to irrigation systems.

To monitor production processes, one requires the determination of the material flows that were required in the product, including by-products and wastes [14]. The environmental footprints—such as water, carbon, and energy ones—support environmental load analyses of production systems through the required material flows and the respective material indices for each approach [15]. In addition, the joint assessment of water and carbon footprints for bio-products is able to provide more accurate insights into the main environmental issues compared to the use of the indicators alone.

The amount of studies on the environmental, economic, and social impacts of agricultural irrigation has grown in recent years [16]. However, most of these studies have addressed the issue of water use for irrigation and not the impact of the irrigation systems' manufacture. Reference [17] investigated the energy demand for assembling irrigation systems. Energy has been an important issue in the environmental debate, although less appealing than carbon since the 2010s. There is a lack of studies on the carbon footprint of the assets of agricultural production [18,19]. The water footprint is an increasing theme, and due to its strong link to irrigation, there is a lack of studies investigating it as an asset for agricultural production, except one by [19].

A study area carried out in Pakistan assessed the energy and carbon footprints of the water supply for irrigation. Surface water presented a smaller footprint (from 3 to 4 kJ m^{-3} for energy, and from 0.22 to 0.30 g m^{-3} for carbon) than groundwater, which required 2100 kJ m^{-3} for diesel pumps and 4000 kJ m^{-3} for electric ones. The carbon footprints were 156 g m^{-3} for diesel pumps and 385 g m^{-3} for electric ones [20].

On rice–wheat production in India, the authors found that substantial nitrogen (from 79 to 114 kg ha^{-1}) and irrigation water (536–680 mm) savings under pressurized irrigation systems allowed for 41 to 64% higher partial factor productivity of nitrogen with a lower (from 48 to 61%) water footprint. The efficient input use caused lower greenhouse gas emissions (39–44%), resulting in a 63 to 76% lower carbon footprint over puddled transplanted rice, followed by conventionally tilled wheat [21]. A study investigated environmental–economic coupled water, energy, and carbon-integrated footprints to assess apple production in China, concluding that the highest environmental footprints were due to the fertilizer production process and irrigation [22]. Recently, a quantitative assessment of the environmental impacts of irrigation projects was published [5]. These authors evaluated 60 typical irrigation projects in northern China. Irrigation, when efficiently managed, can save water; on the other hand, higher yields, water consumption, and greenhouse gas emissions during the manufacturing and assembling of the irrigation systems can negatively affect environmental health [5]. Measurements of the energy and carbon footprints of irrigation systems, with the widespread adoption of low-energy precision applications in the Kansas region, showed a reduced energy footprint and equivalent carbon emissions of about 20% [23].

Although there have been many studies on the water and carbon footprints of agriculture, many of them have focused only on the use of energy for pumping and the consumption and scarcity of surface water, or they have focused on evaluating how irrigation changes the carbon dynamics in the soil. Few studies have evaluated the impact caused by the manufacture of the components of irrigation systems.

Further studies are needed to address gaps and to determine how to increase energy efficiency in irrigation systems in the future. Additionally, it is crucial to link the adoption of these technologies and practices to policies that encourage water consumption reduction, which ultimately leads to reduced energy use and carbon emissions.

To fill this gap, this study aimed at determining the water and carbon footprint of two systems of irrigation—drip and center pivot. Their components were detailed, and the impact of irrigation projects considering the materials used was quantified. The considered variables of irrigation projects were: the irrigated area, the flow of the system, the energy required for pumping, and the pipeline length from the water source and irrigation system. In addition, depreciation was approached to analyze different scenarios.

By establishing life-cycle indices and assessing the impact of irrigation systems on the water and carbon footprints, we hope to contribute to a more comprehensive understanding of the environmental impacts of agriculture and provide valuable information for decision-making regarding the choice of more sustainable irrigation systems.

2. Materials and Methods

The current study was based on the physical basis, also known as the material flows, of the center pivot and drip irrigation systems developed by [17], who determined the energy footprint of such systems. This evaluation did not consider the operational aspects of the considered systems since they can vary due to climate, crop, and soil variations. So, the power sources to operate them are not included.

2.1. Limit and Assumptions

The upstream phase regarded the manufacturing of irrigation systems' components, such as pipes, filter emitters, and pumps. Irrigation systems were divided into their constituent parts considering the different designs and different useful lives of the equipment.

In this research, water applied to irrigated crops and greenhouse gas emissions from energy and pumping requirements were not considered due to the variability they have among crops and weather conditions. So, irrigation water and energy consumption (electricity or diesel oil) were not considered in the studied footprints.

2.2. Characteristics of Irrigation Systems and Material Flows

Water and carbon footprints originating from irrigation systems can be determined through the footprint indices of every material required for this system to be set. These indices vary depending on the irrigation systems and the total irrigated area.

For the carbon and water footprints to be determined in the supply chain, irrigation systems were divided into their subsystems, for which the respective material flows were determined. This phase required that the materials of all parts were identified. Due to the importance of properly assessing the material composition, the material flows published in [17] were adopted.

We considered different useful life values for the drip lines and center pivots. The service life was fixed for other components of these systems since equipment material can influence the depreciation period. Initially, the indices for the pumps and main pipes were determined because both are common components of all types of irrigation systems. For the main pipe, the materials considered were galvanized steel and polyvinyl chloride (PVC).

For water supply piping in irrigation systems, the amount of water and carbon incorporated is affected by two main factors: length and flow. For flow, the related factors are the thickness of the pipe and the different levels of pipeline pressure correlated with the maximum level along the pipeline. To determine the pressure at any point in the pipeline, it is necessary to consider the pressure drop in the pipeline between the starting point and the desired point, the difference in height between these points, and the pressure required at the endpoint of the pipeline [16]. Therefore, these factors must be considered in the footprint calculations, as the different pressure classes will result in different masses per meter of pipe. Thus, to determine the appropriate diameters and mass of the tubes, we used the guidelines from [16]. In this research, the total depreciation period for both the PVC and galvanized pipes was taken as 20 years [24].

2.2.1. Drip System

In drip systems, the wall thickness of the tube is influenced by the useful life, and the main components of the internal irrigated area are the drip lines. This influence on useful life was observed when the tubes were laid on the soil surface. On the other hand, this effect was not observed when the tubes were installed under the soil surface.

A variable also considered was the irrigated area, which included spaces between the drip lines and/or between the drippers. Additionally, in drip systems, it is also required to provide water filtration. Two kinds of filters—sand and automatic—were evaluated. For the internal irrigated area, twelve different irrigation projects [17] (5–215 ha) were evaluated, presenting material consumption as being correlated to the irrigated area.

2.2.2. Center Pivot

For the center pivots, the irrigated area was determined due to the diameter, representing the total length of the center pivot. Only the center pivot was considered, neglecting the use of end guns.

For the center pivot, the simulations followed the recommendations of [17] for the equipment of five assembled sets and considered the number of mobile towers, ranging areas from 11 to 158 ha, with no system for corner irrigation considered. The equipment mass was obtained from data supplied by a domestic irrigation company (Brazil) and a manufacturer's catalog.

2.3. Carbon and Water Footprint Calculations

The water and carbon footprints used to manufacture and assemble a given irrigation system can be determined by the indices of all materials required in this given irrigation system (Equation (1)). The indices may vary due to the type of irrigation systems and the irrigated area (A).

$$\text{WF or CF} = \frac{1}{A} \sum \frac{M_1 \times if_1}{L_1} + \frac{M_n \times if_n}{L_n} \quad (1)$$

where CF is the carbon and WF is the water footprint of irrigation systems (kg or m^3 ha^{-1} yr^{-1}), Mn is the mass of the nth material required by the irrigation system (kg), if_n is the embodied water consumption or carbon emission indices of the nth material (kg or m^3 kg^{-1}), L_n is the depreciation period of the nth material required by the irrigation system (year), and A is the area under irrigation (ha).

2.3.1. Blue Water Footprint Coefficient

Only the blue water footprint was considered in this study. The green water footprint is usually minute in manufacturing processes, except when bio-based materials are required.

The indicators of the embodied water per mass used are shown in Table 1. All inputs are represented by their measurement unit (kg or L), and their respective water requirements were obtained from references, whose results are shown in m^3.

Table 1. Indices for blue water footprint of materials used in irrigation systems.

Material	Blue Water Footprint Coefficient ($L\ kg^{-1}$)	References
Steel	10.0	[25]
Polyvinyl chloride tube	10.0	[26]
Low-density polyethylene tube	13.7	[27]
Sand	7.5	[28]
Iron-forged	1.3	[29]

2.3.2. Carbon Footprint

For the carbon footprint estimation, the emission factor of all inputs was obtained from references for the emissions to be estimated (Table 2).

Table 2. Indices for carbon footprint of materials used in irrigation systems.

Material	Carbon Footprint Coefficient ($kg\ kg^{-1}$)	References
Steel	3.19	[30]
Polyvinyl chloride tube	3.00	[31]
Low-density polyethylene tube	1.60	[31]
Sand	3.40	[32]
Iron-forged	0.75	[33]

Likewise, after estimating emissions from direct inputs, their sum (Equation (1)) provides the carbon footprint of the life cycle.

3. Results

In this section, the equations for the material flows of the components of the irrigation systems are presented and translated into water and carbon footprints. In pumping systems, a correlation between the carbon and water footprints and the power requirements was observed (Figures 1 and 2), similar to the findings of an evaluation of the incorporated energy [17]. The mass of the pumps increased according to their power requirement, which caused the correlation also observed with the carbon and water footprints.

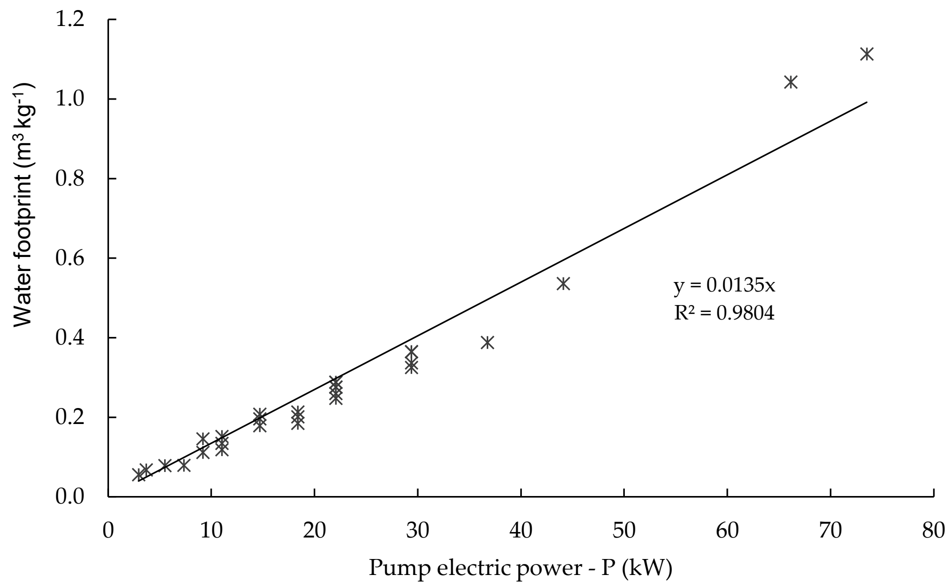

Figure 1. Water footprint correlated to pumping power requirement.

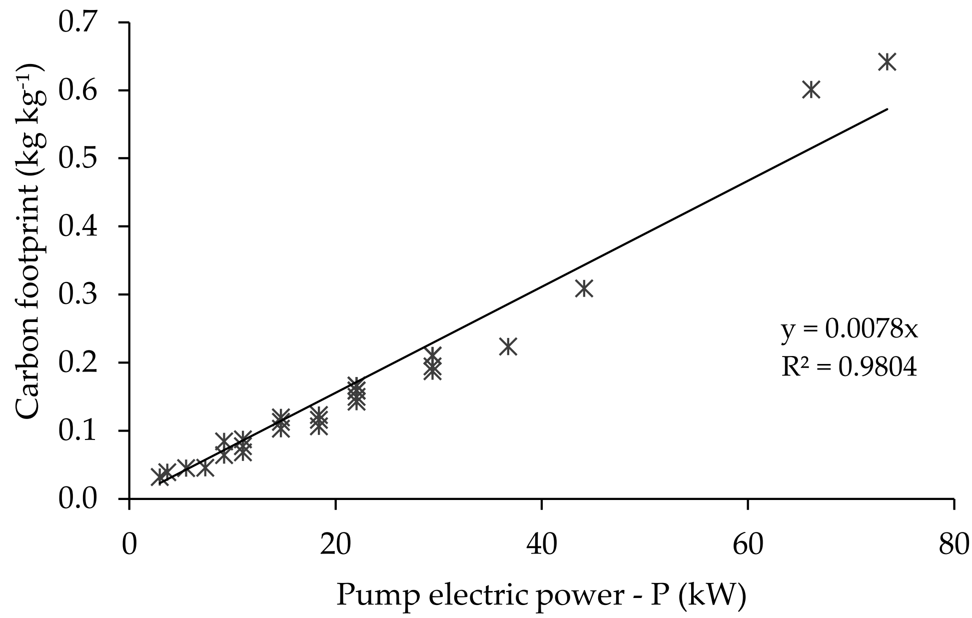

Figure 2. Carbon footprint correlated to pumping power requirement.

Since the behavior of the water and carbon footprints were similar, from now on, only a single figure is presented for every component of the irrigation systems for the sake of saving space in the manuscript. To provide the readers with the data of the missing figure, the equations obtained for carbon footprint are presented. The water footprint (Figure 3) and carbon footprint of the pipeline were determined as a function of the material flow of the pipe. These values were obtained through the variation and/or inclination of the pipe, obtaining the maximum, minimum, and average values of the carbon and water footprints per meter of pipe. The changes in the pipe diameters resulted in level changes in the carbon and water footprints (Figure 3).

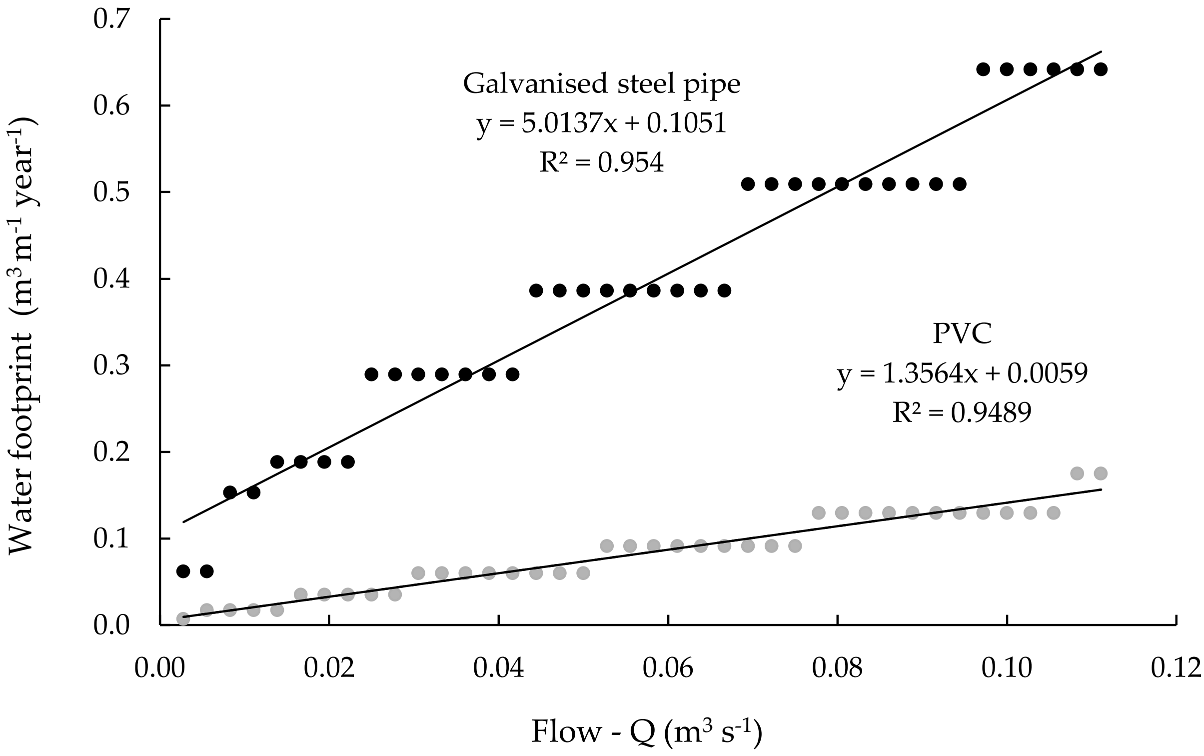

Figure 3. Specific water footprint per pipe length and lifetime correlated to flow.

It is important to highlight that the values shown in Figure 3 and Equations (2) and (3) (respectively, the carbon footprint of PVC pipes and the carbon footprint of galvanized steel pipes) are expressed per meter of pipe, so the footprint depends on the total length of the pipeline.

In this study the difference between the carbon footprint per meter of pipe when the flow was 0.02 $m^3\ s^{-1}$ was 0.055 kg $CO_2\ m^{-1}\ year^{-1}$, and for the water footprint, it was 0.17 $m^3\ m^{-1}\ year^{-1}$ lower for the PVC pipe. However, when a flow of 0.10 $m^3\ s^{-1}$ was considered, this difference for both footprints was 2.7 times higher for the steel pipe.

$$CFP_{steel} = 1.599\ Flow + 0.0335 \quad (2)$$

$$CFP_{PVC} = 0.4081\ Flow + 0.0017 \quad (3)$$

where CFP_{steel} = the specific carbon footprint per steel pipe length and lifetime correlated to flow (kg $m^{-1}\ year^{-1}$), CFP_{PVC} = the specific carbon footprint per PVC pipe length and lifetime correlated to flow (kg $m^{-1}\ year^{-1}$), and flow ($m^3\ s^{-1}$). The R^2 values obtained were 0.954 (Equation (2)) and 0.9487 (Equation (3)).

In addition, the filter was another component of the irrigation systems that showed differences in the carbon and water footprints due to the material. Two types of filters were considered: sand (sandfill) and automatic screen filters (Figure 4, Equations (4) and (5)). The sand filter presented the highest carbon and water footprints. This was due to the steel mass of the sand filter, even with a longer life than the automatic screen filter.

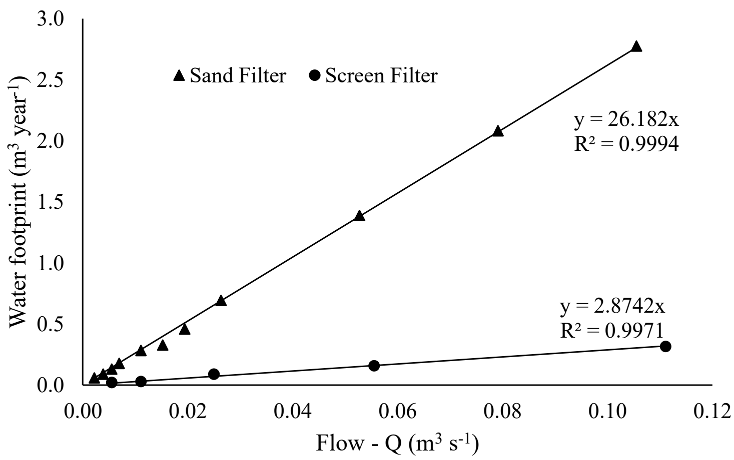

Figure 4. Annual water footprint of filtering correlated to flow.

The annual carbon footprints of the sand (Equation (4)) and screen filters (Equation (5)) obtained, respectively, R^2 values equal to 0.9993 and 0.9971.

$$CF_{sand} = 3.5734\ \text{Flow} \quad (4)$$

$$CF_{sand} = 3.9169\ \text{Flow} \quad (5)$$

where CF_{sand} = the annual carbon footprint of sand filtering correlated to flow (t year^{-1}), and CF_{sand} = the annual carbon footprint of screen filtering correlated to flow (t year^{-1}).

The water footprint (Figure 5) and carbon footprint (Equation (6)) are presented as a result of the wall thickness of the drip tube with distinct estimated depreciation and distance between tube lines. For the drip irrigation system, little variation of 0.0069 kgCO_2 ha^{-1} year^{-1} in the carbon footprint was observed, and for the water footprint, the variation was 0.0024 m^3 ha^{-1} year^{-1} when the area was varied and, consequently, the distance between the tube lines and the type of drip tube was adjusted.

$$CF_{drip} = 13.925\ \frac{t}{UL}\ s^{-0.95} \quad (6)$$

where CFdrip is the carbon footprint of the internal part of drip irrigation (t ha^{-1} year^{-1}) for different depreciation periods, UL = the useful life (year), s = the distance between drip lines (m). Equation (6) obtained an R^2 value of 0.98.

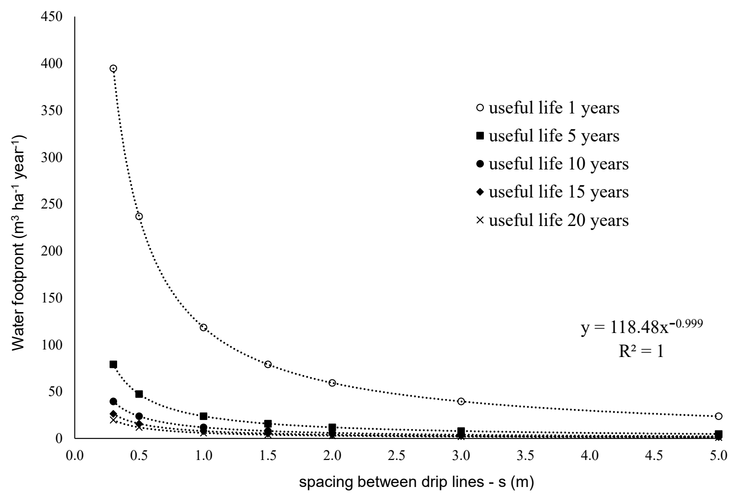

Figure 5. Specific water footprint due to distance between tube lines.

Drip irrigation showed that the water footprint was influenced by the size of the irrigated area, increasing as the unit of area decreased (Figure 6, Table 3, and Equation (7)). Similarly, the carbon footprint of the center pivot was determined by Equation (8).

$$WF_{inpivot} = \frac{18.708}{UL}\, A^{-0.501} \tag{7}$$

where $WF_{inpivot}$ = the water footprint of a center pivot with five different useful life values, without corner system ($m^3\ ha^{-1}\ yr^{-1}$).

$$CF_{inpivot} = \frac{0.5968\ \mathrm{t}}{UL}\, A^{-0.501} \tag{8}$$

where $CF_{inpivot}$ = the carbon footprint of a center pivot with five different useful life values, without corner system t $ha^{-1}\ yr^{-1}$).

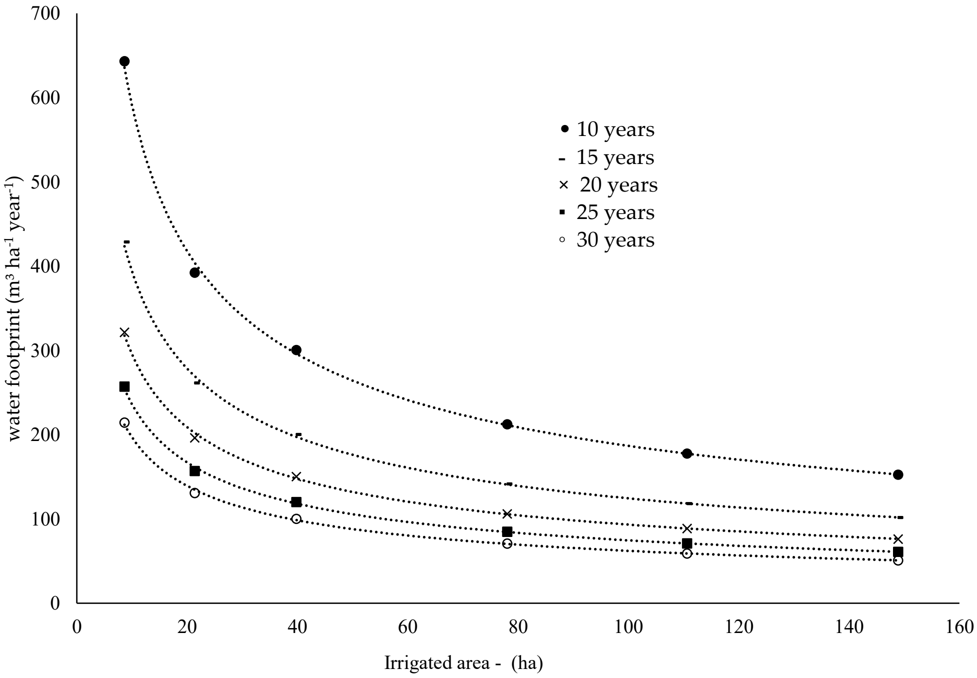

Figure 6. Specific annual water footprint per area for center pivot with five different useful life values, without corner system.

Table 3. Regression equations for water footprint estimation for distinct depreciation periods of center pivots.

Depreciation Period Year	Water Footprint (y) Due to Irrigated Area (x) $m^3\ ha^{-1}\ yr^{-1}$
10	$y = 1870.8x^{-0.5}$
15	$y = 1247.2x^{-0.5}$
20	$y = 935.38x^{-0.5}$
25	$y = 748.31x^{-0.5}$
30	$y = 623.59x^{-0.5}$

The water footprints of center pivot and drip systems were modeled by applying the results obtained and their correlations. For the internal part of the center pivot ($W_{inpivot}$) and drip irrigation systems (W_{indrip}), the water footprint was determined per unit of irrigated area. However, for pumping systems, the pipeline and the filtering systems were divided by the irrigated area (A) in Equations (9)–(12) because they were initially determined as the volume per time period ($m^3\ year^{-1}$).

$$CF_{drip} = \left[\left(\frac{13.925 * t}{UL}\right) * S^{-0.99}\right] + \left(\frac{0.4069 * Q + 0.0018 * L + 0.9169 * Q + 0.078 * P}{A}\right) \quad (9)$$

$$CF_{pivot} = \left[\left(\frac{0.5968 * t}{UL}\right) * A^{-0.501}\right] + \left(\frac{0.4069 * Q + 0.0018 * L + 0.078 * P}{A}\right) \quad (10)$$

$$WF_{drip} = \left[\left(\frac{118.48 * t}{UL}\right) * S^{-0.99}\right] + \left(\frac{1.35 * Q + 0.0059 * L + 2.8742 * Q + 0.0135 * P}{A}\right) \quad (11)$$

$$WF_{pivot} = \left[\left(\frac{18.708}{UL}\right) * A^{-0.501}\right] + \left(\frac{1.35 * Q + 0.0059 * L + 0.0135 * P}{A}\right) \quad (12)$$

Equation (11) was used to calculate the water footprint of a drip irrigation system using PVC tubes and an automatic screen filter, disposed over the soil surface. The irrigated area for center pivot systems, pumping systems, and pipelines influenced the water footprint of the internal part of the system (Equation (12)).

4. Discussion

It can be noticed that the water and carbon footprint incorporated for PVC pipe (WFpvc) was lower than the one for galvanized steel pipe (WFsteel). So, as suggested by [17] for the energy footprint, an alternative for decreasing the water footprint of irrigation systems is to consider that for pressure levels above 1250 kPa, the adoption of galvanized steel is mandatory, and below this pressure level, the adoption of PVC (polyvinyl chloride) is possible. One must consider a combination of the two materials in irrigation systems.

Regarding the carbon footprint of materials for civil construction, water transmission, or sewage systems, there have been several studies in the last few years. Some of these studies have evaluated and compared the different pipe materials. Reference [33] evaluated pipes and liners used in the construction industry in the United States. At the manufacturing stage, the equivalence of CO_2 emissions from a cured-in-place casing pipe was nearly six times the amount of carbon compared to a prestressed concrete cylinder pipe. PVC pipe was the material with the second-lowest carbon footprint in the manufacturing phase.

A comparison between two types of material applied for large-diameter water transmission showed that steel presented a 32% higher impact than concrete due to the higher energy requirement for manufacturing. That study evaluated four phases, including the life cycle, material production and fabrication, transport, and installation of the pipeline [34].

The results of the emissions throughout the life-cycle of a project for underground potable exploitation indicated that molecularly oriented PVC (PVC-O) presented better environmental performance compared to regular PVC, ductile iron tubes, and high-density polyethylene (HDPE) tubes [35].

The magnitude of the difference between the carbon and water footprints of the filters at a flow rate of 0.055 $m^3 s^{-1}$ was eight times. This difference is due to the material incorporated by each type of filtering system and may vary depending on the desired water quality in the irrigation project. In addition, other alternatives can be used to improve the water quality.

The useful life of the materials generated, independently of the area, a reduction of around 50 and 67% in the water footprint when the depreciation period varied from 10 to 30 years, respectively. The same result was observed by [17] when evaluating the embodied energy. To summarize the equations for different useful lives (Table 3), Equation (7) was established, incorporating the depreciation period into the model, obtaining an R^2 of 0.99.

For the drip system, as the increase in the amount of drip lines was proportional to the irrigated area, it did not influence the water footprint. The same behavior was observed by [17] when evaluating the energy incorporated by the irrigation systems. It was observed that due to the amount of mass incorporated into the system, the distance between the irrigation lines and the thickness of the walls of the dripper tubes affected the water footprint. In addition, the useful life of materials must be considered in the life-cycle inventory of irrigation systems as it has a great impact on the results.

In India, a study determined the water footprint of each component accounting for water consumption in the supply chain to produce raw materials and operational water use in the micro-irrigation system manufacturing process [36]. The results observed for the total blue water footprints ranged from 0.4 L kg^{-1} for drip tubes to 4.0 L kg^{-1} for PVC molded fittings. The authors highlighted that most of the supply chain and total water footprint was blue water associated with raw material production. Data to calculate the grey water footprint associated with the production of raw materials (plastics) were not available, so this component is unknown.

Evaluations of water and carbon footprints of irrigation projects in China using life-cycle assessment (LCA) methods were performed [20]. The results of 60 usual irrigation projects in northern China presented that the water footprint accounted for a small share of them, reaching from 0.2 to 1.5% of the total agricultural water footprint. However, these authors also considered the water usage in the agricultural phase. Regarding the carbon footprint, the authors observed that as the investment of the project increased, the carbon footprint also increased. The carbon footprint per sprinkler, considered as an irrigation unit, was higher than those of the drip irrigation and pipeline projects because the manufacturing and operation of sprinkling irrigation projects require more energy, machinery, and labor.

An evaluation performed on irrigation systems, with the widespread adoption of low-energy precision application in Kansas, observed that direct energy consumption for pumping is the main driver of the carbon footprint [23].

5. Conclusions

The model developed to calculate the water and carbon footprints based on the material requirements of the irrigation systems allowed us to observe the main factors that affected the environmental performance of the evaluated irrigation systems. The size of the irrigated area affected the water and carbon footprint differently. This difference was due to the fact that when increasing the irrigation area, the same increase did not occur proportionally for the water and carbon emissions of the central pivot and drip systems.

The results presented can compose a life-cycle database. In addition, they may allow decision-makers to check, using life-cycle assessment, the effects on the water and carbon footprints of irrigation systems in order to manage how their use would affect crop production. Discussions on the value of water and its use being competed by industries, population, and biomass production can gain complexity as new approaches become sensitive to the stakeholders.

Further studies may investigate the operational aspects of the evaluated irrigation systems contextualized by crop requirements and power sources and incorporate recycling possibilities based on the material applied and the operation required for removing the depreciated equipment (e.g., drip installed below the soil surface).

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