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Gray and White Water Footprint Estimation in a Greenhouse Production

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Abstract

Optimizing water use in agriculture is crucial for sustainable resource management and increased productivity. Water footprint analysis, which measures the total water used directly and indirectly throughout a product's life cycle, offers valuable insights for improving water management practices. This study investigated the gray and white water footprints of a greenhouses cultivation, bell pepper, under different conditions including misting and pot cover. Evapotranspiration rates were used to calculate water demand under various scenarios. Nitrate (NO_3), potassium (K), and total phosphorus (TP) were monitored as key chemical parameters to calculate the gray water. Three scenarios including stringent (S1), normal (S2), and lenient (S3) are established based on water quality standards. The findings revealed that misting and covering pots significantly reduced the gray water footprint compared to non-misting or uncovered scenarios. The total gray water footprint for bell peppers under misting and covered conditions was 2976 m^3/ton, while it reached 3968m^3/ton under non-misting and uncovered conditions, this represents a reduction of nearly 33% due to the combined effect of misting and pot cover. Importantly, water quality standards also played a significant role, with stricter standards leading to a higher gray water footprint (e.g., a difference of 2655m^3/ton between scenarios S1 and S3 under misting and covered conditions).The white water footprint, representing freshwater directly used for cultivation, also varied across different scenarios.

Keywords: Bell Pepper, Gray Water Footprint, Greenhouse Cultivation, Irrigation, White Water Footprint.

1. Introduction

The escalating global population and the ever-increasing demand for agricultural production, directly linked to food security, have intensified the challenge of water scarcity (Razavi & Davari, 2013). As agriculture remains the primary source of food, and water the most critical limiting factor in its development, effective water resource management has become more crucial than ever (Behmanesh, 2016). The rise of international trade and the concept of "virtual water" have shifted research focus towards understanding the water footprint of products and water import/export patterns (Rahimi, 2021; Aligholinia et al., 2019). Since water consumption and footprint vary significantly based on climate, agricultural practices, and water use efficiency in different regions, accurate estimation methods are essential (Hoekstra, 2011). The water footprint index, which captures water consumption based on regional conditions and climate, has emerged as a valuable tool.

The water footprint comprises four components: blue (surface and groundwater extraction), green (rainwater stored in soil), gray (freshwater used to dilute pollutants), and white (water lost through plant transpiration) (Rahimipour Anaraki et al., 2022; Ababaei and Etedali, 2014). Introduced by Hoekstra (2003), the water footprint index has been employed by numerous researchers to assess actual water use across various sectors, including agriculture, industry, households, livestock farming, and others (e.g., Kalvani et al., 2019; Azam et al., 2012; Xu et al., 2015; Wang et al., 2023; Cao et al., 2023; Gao et al., 2023; Mehla et al., 2023; Piri and Sarani, 2020; Khalili et al., 2019). Previous studies have explored the water footprint of various crops and the impact of agricultural practices on water use efficiency (Novoa et al., 2019). For instance, Zhuo and Hoekstra (2017) demonstrated that deficit irrigation significantly increased blue water use efficiency for winter wheat, resulting in a 5% rise in irrigation efficiency and a 38% reduction in blue water footprint. Similarly, Aligholinia et al. (2017) analyzed the water footprint of major crops in the Urmia Lake Basin, highlighting wheat as the crop with the highest water footprint, reaching 1779 m^3/ton for blue water, 730 m^3/ton for green water, and a total of 2511m^3/ton.

Novoa et al. (2023) assessed the water footprint of 21 crops in central Chile, broken down into its components (blue, green, and gray), over two consecutive years (2017-2018). The results showed that the green and gray water footprints increased significantly in the south-central basins, while blue water consumption increased in the central zone basins, indicating a transition in water footprint based on latitude and climate conditions. It also indicated that virtual water flows increased by 44% annually, with connections established between origins and destinations. Asia, Europe, and North America were the preferred destinations, with variations in exports of specific crops like apples, cherries, grapes, blueberries, and walnuts. The study highlights the importance of sustainable agriculture in a commodity exporting country facing water deficit problems and the need for improved water distribution and local water policies.

Li et al. (2023) conducted a research focused on estimating the water footprint (WF) and assessing the sustainability of wheat and maize production in Henan Province, in China. By utilizing global water footprint benchmark values for different crops, the study calculated benchmark values for blue water footprint (BWF) of major crops, establishing optimal and sub-optimal levels for comparison. The results revealed that the average annual blue water footprint of wheat production in Henan Province was 7914 MCM, with 77% considered unsustainable, while maize production had a blue water footprint of 703 MCM, with 70% deemed unsustainable. The study also estimated potential blue water savings by reducing crop-specific BWF to different benchmark levels. For wheat production, saving approximately 2742 MCM or 375 MCM of blue water was possible by reaching optimal or sub-optimal benchmark levels, respectively.

Bell peppers, a seasonal product that is consumed globally and holds significant economic and nutritional value, are commonly grown either in open fields or in greenhouses. The main objective of greenhouse cultivation is to increase agricultural production per unit area by increasing inputs. In 2020, the export value of bell peppers surpassed $6.1 billion, underscoring its economic importance (Kabir et al., 2021). The leading producers of bell peppers are the United States, Mexico, China, and Indonesia, collectively cultivating over 530 hectares of land (Anaya-Esparza et al., 2021; Flores-Velazquez et al., 2022).

Padrón et al. (2016) explored the water requirements of bell pepper (Capsicum annuum L.) in five municipalities of Rio Grande do Sul-Brazil. The study aimed to estimate supplemental irrigation depths in bell pepper crops across five municipalities. Climatic variables were analyzed over 20 years, with 15 years selected for each location. Soil data was collected through field observations and laboratory testing. The WinISAREG® simulation model was utilized for the study. Results showed that the maximum simulated evapotranspiration across all municipalities was 529.74 mm. On average, the irrigation depth required for all municipalities and planting dates was 365.7 mm. In Iran, around 145,000 tons of bell peppers were exported in 2020, primarily originating from regions such as Isfahan, Tehran, and the southern provinces (Moosavi et al., 2023). Although greenhouse cultivation offers water savings compared to open fields, there are still challenges related to freshwater usage, wastewater production, and water quality deterioration in Iran (Moosavi et al., 2023). Accurate estimates of water consumption throughout the lifecycle of a product are crucial for efficient resource management. The concept of water footprint, as highlighted by Allan (1993), plays a pivotal role in this aspect. Greenhouse production raises specific concerns regarding point-source pollution and the generation of large volumes of wastewater (Tabatabaei et al., 2014). Therefore, it becomes imperative to determine the gray water footprint in order to assess the environmental impact of greenhouse cultivation.

Building upon existing research and recognizing the importance of water footprint analysis in agricultural sustainability, this study aims to estimate and evaluate the gray and white water footprints of a greenhouse production as bell pepper cultivation. The contribution of this research involve the gray and white water footprints of bell pepper in greenhouse in Iran by experimentally determining the evapotranspiration rate, pollutant levels, and water losses within the plant tissue. The determination of pollutant levels encompass meticulous measurement of various water quality parameters such as nitrate (NO3), potassium (K), and total phosphorus (TP) at regular intervals throughout the cultivation cycle to capture potential variations. Measurement of water losses within the plant tissue involve quantifying the transpiration rate of bell pepper plants at different growth stages. Finally, the water footprint of greenhouse bell pepper cultivation are assessed based on alternative scenarios.

2. Materials and Methods

This study is conducted in two hydroponic greenhouse halls with bell pepper production covering an area of one hectare, located at Varamin city (35°21′03″N- 51°38′09″E) in central part of Tehran province, Iran. This greenhouse comprises two halls with a combined area of 10,000 m². Each hall measures approximately 115.2 meters in length and 42.5 meters in width. Figure 1 shows the plan of the greenhouse. The region has a dry climate with low rainfall, high temperatures, and long dry periods. The highest rainfall occurs in winter, while the lowest is in summer. Greenhouse cultivation begins in spring. The irrigation system in the greenhouse is drip irrigation. Irrigation is carried out based on the daily water exit flow measurement with stocking of nutrients in two 500-liter tanks in odd and even days, as well as utilizing two 10,000-liter tanks. The input water passes through a sand filter in the water collection tanks, and a disc filter is used at the outlet. The water used in this irrigation system is supplied from the well in the greenhouse town.

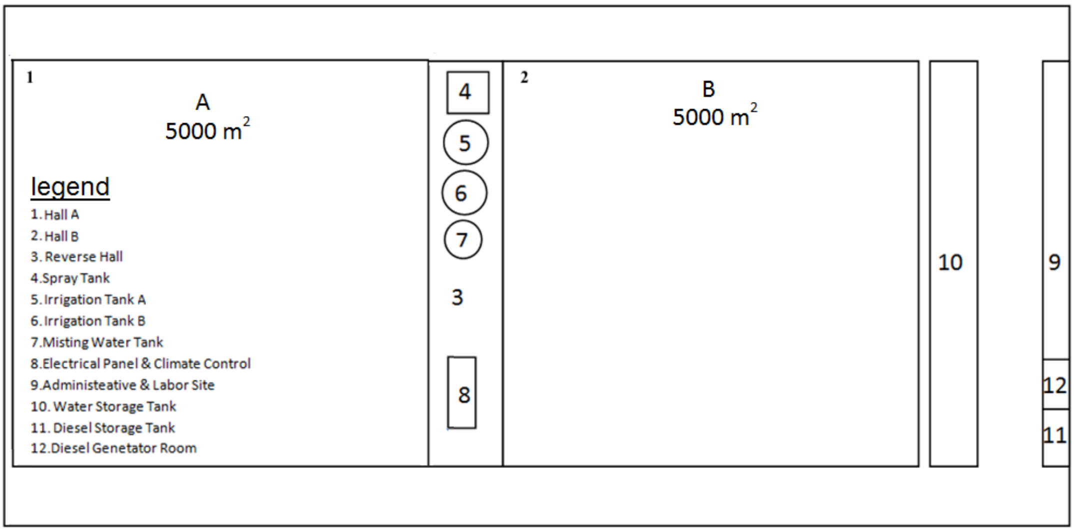

Fig. 1. Plan of the studied greenhouse halls in Varamin city, showcasing the overall structure, ventilation systems, and potential presence of equipment relevant to the research (e.g., irrigation tanks).

The temperature and humidity regulation system in the greenhouse is smart so that the temperature does not drop below 18 degrees Celsius in the coldest conditions and reaches 30 degrees Celsius in the hottest conditions. Also, the humidity is always kept constant at approximately 65%.

This experiment utilized Avanté variety pepper seedlings, chosen for their superior cold and heat resistance compared to other available options. The cultivation setup employed plastic drainage pots (size 10) and specialized containers to collect drainage from each pot. Twelve pots were distributed across two conditions: with misting and without misting. Within each condition, three pots were further equipped with covers to minimize soil surface evaporation.

Three key chemical parameters were monitored throughout the experiment: nitrate (NO_3), potassium (K), and total phosphorus (TP). Nitrate concentration was measured using the standard UV spectrophotometric screening method 4500-NO_3-B. Potassium levels were determined through the flame photometer method. Finally, total phosphorus was assessed using the digestion method, with readings taken at a specific wavelength according to standard method 4500-P-E.

2.1. Gray water footprint

The gray water footprint, a component of the water footprint concept, assesses the environmental impact of agricultural production on water quality. It represents the volume of freshwater needed to dilute pollutants, primarily fertilizers and pesticides, to acceptable levels. Equation 1 calculates the gray water footprint for each individual pollutant (*i*) in m^3/ton. The maximum value obtained from considering multiple pollutants using Equation 2 represents the overall gray water footprint (Hoekstra and Chapagain, 2008).

$$WF_{gray} = \frac{(\alpha * NAR)}{(C_{Max} - C_{Nat})} * \frac{1}{Y} \quad (1)$$

$$GWF = Max(GWF)_i \quad (2)$$

where WF_{Gray} represents the gray water footprint in (m^3/ton), *Y* denotes the crop yield (ton/ha), α (%) indicates the percentage of fertilizer losses, *NAR* (kg/ha) stands for the consumption rate of each fertilizer per plant, C_{max} represents the maximum permissible critical concentration for the desired chemical parameter (kg/m^3), and C_{nat} is the background concentration of the chemical parameter (kg/m^3) in the recipient water sources.

2.2. White water footprint

The white water footprint, a relatively new concept, quantifies irrigation water losses during crop production. Equation 3 (Ababaei and Etedali, 2014) calculates this indicator:

$$WF_{white} = \frac{CWU_{gblue} - CWU_{blue}}{Y} \quad (3)$$

$$WWF_{unaccounted} = WWF_{WTP} \quad (4)$$

$$WWF_{WTP} = \frac{WTP}{Y} \quad (5)$$

$$MWWF = WF_{white} + WWF_{unaccounted} \quad (6)$$

where CWU_{blue} is the net irrigation requirement of the studied crop (m^3/ha), CWU_{gblue} is the gross irrigation requirement of the studied crop (m^3/ha), *YY* is the crop yield (ton/ha), and *WFwhite* is the white water footprint resulting from irrigation losses (m^3/ton). Additionally, this study further proposes the concept of white water footprint within plant tissue. This component, denoted as *WWFWTP* (m^3/ton), represents the unaccounted water loss through transpiration. The adjusted white water footprint (*MWWF*) takes both components into account.

2.3. Maximum Permissible Concentration (C_{max}) and Background Natural Concentration (C_{nat})

Determining the maximum permissible concentration (MPC) for pollutants is crucial for calculating the gray water footprint. However, as this is a global indicator, a single value may not be universally applicable. This study addresses this challenge by considering multiple water quality standards from various regions worldwide. Three scenarios are established based on these standards: stringent (S1), normal (S2), and lenient (S3). The specific pollution indices for each scenario are detailed in Table 1. To calculate the background concentration, the water quality of the greenhouse well was tested. The quality of chemical parameters tested in this study is presented in Table 2.

Table 1. Various Scenarios for C_{max} (Iran Environmental Organization, 2015; MEP-PRC, 2002; CCME, 2010)

Parameter (unit)	Scenario	C_{max}	standard
NO_3(mg/L)	S_1	2.9	Canadian Water Quality Guidelines for the Protection of Aquatic Life
	S_2	11.3	Iranian Drinking Water Quality Standard
	S_3	20	Surface Water Quality Standard Level III, China
K(mg/L)	S_1	12	European Union Water Quality Standard (EC, 2006)
	S_2	12	
	S_3	12	
TP(mg/l)	S_1	0.13	Iran's Level I Water Quality Standard for Aquatic Environmental Conservation
	S_2	0.3	The European Union's Surface Water Quality Standard for Drinking Water Withdrawal
	S_3	1	OECD Surface Water Quality Regulations (OECD, 2008)

Table 2. Background concentration (C_{nat}) of chemical parameters (mg/l) in the present study.

Parameter	TP	K	NO_3
C_{nat}	0.025	3.3	2.4

2.4. Water content in plant tissue

This study employs a gravimetric method to determine the water content in plant tissue and crops. Duplicate samples of a specific weight are collected and weighed (W_1) before drying for 24 hours. Following drying, the samples are weighed again (W_2). Equation (7) is then used to calculate the water content (W_{wat}):

$$W_{wat} = \frac{W_1 - W_2}{W_{1net}} * W_c * 10^{-3} \quad (7)$$

where, W_{wat} represents the amount of water present in the desired product (plant tissue or crop tissue) per cubic meter per hectare, W_1 is the weight of the sample of the desired product along with the container before drying in kilograms, W_2 is the weight of the sample of the desired product along with the container after placing it in it in kilograms, W_{1net} is the net weight of the tested product sample (excluding the weight of the container) in kilograms, and W_c is the total weight of the studied product in kilograms per hectare.

3. Results and Discussion

3.1. Grey water footprint

In this study, the grey and white water footprint of greenhouse bell pepper cultivation were evaluated. Grey water footprint was calculated for each pollutant under various scenarios of water quality standards, and the amount of white water footprint of bell peppers was estimated. Since water was used for the growth of plant tissue of the studied crop, in order to determine the amount of water wasted due to these factors, modified equations for calculating white water footprint were introduced, and a new concept called unaccounted white water footprint was introduced. Finally, based on the results obtained from the amount of water inside plant tissue, the white water footprint was calculated. Grey water footprint was analyzed and compared under different scenarios of water quality standards, including scenarios S1, S2, and S3, as well as under four conditions: misting with cover, misting without cover, non-misting with cover, and non-misting without cover. Misting is one of the most common systems used in greenhouse halls for cooling the air during the hot seasons, preventing overheating, and providing sufficient moisture for plants in greenhouses.

This is because in greenhouse environments, excessive temperature and low humidity reduce the yield of crops. Evaporation increases with rising air and soil temperatures and decreasing relative humidity. Therefore, placing covers on the surface of pots aims to reduce evaporation from the surface of the pots by preserving soil moisture. Since the decrease in air and soil humidity affects the crop yield, and considering the indirect relationship between the amount of grey water and the crop yield (Y), these conditions can affect the increase or decrease in the amount of grey water. According to the results presented in Figure 2, the total grey water footprint of bell peppers in misting conditions with cover was 2976, 1136, and 320.5 m^3/ton for scenarios S1, S2, and S3, respectively. In misting conditions without cover, it was 3246.8, 1239.7, and 349.7 m^3/ton for scenarios S1, S2, and S3, respectively.

Moreover, in non-misting conditions with cover, the grey water footprint was 3571.4, 1363.6, and 384.6 m^3/ton for scenarios S1, S2, and S3, respectively. Finally, for non-misting conditions without cover, it was 3968.3, 1515.2, and 427.4 cubic meters per ton for scenarios S1, S2, and S3, respectively. This means that water quality standards (C_{max}) have a significant impact on increasing the final grey water footprint, so that, for example, in misting conditions with cover, there is a difference of 2655.7 m^3/ton between scenarios S1 and S3. Additionally, under misting conditions, the grey water footprint is lower compared to non-misting conditions due to the increase in humidity and its effect on the crop yield. Moreover, covering the surface of the pots significantly (9-11%) reduces the grey water footprint because it preserves the moisture present in the pots and affects the increase in crop yield.

The findings depicted in Figure 3 highlight that among the three scenarios S1, S2, and S3, total phosphorus emerges as the most critical pollutant, alongside nitrate and potassium. Moreover, the grey water footprint can fluctuate under varying water quality standards. For instance, in scenario S1, with misting irrigation and pot covers, the grey water footprint of nitrate (1518.8 m^3/ton) surpasses that of potassium (109.2 m^3/ton). Conversely, in scenarios S2 and S3, the grey water footprint of potassium outweighs that of nitrate. These evaluations underscore the influence of alterations in water quality standards and different pollutants on the grey water footprint.

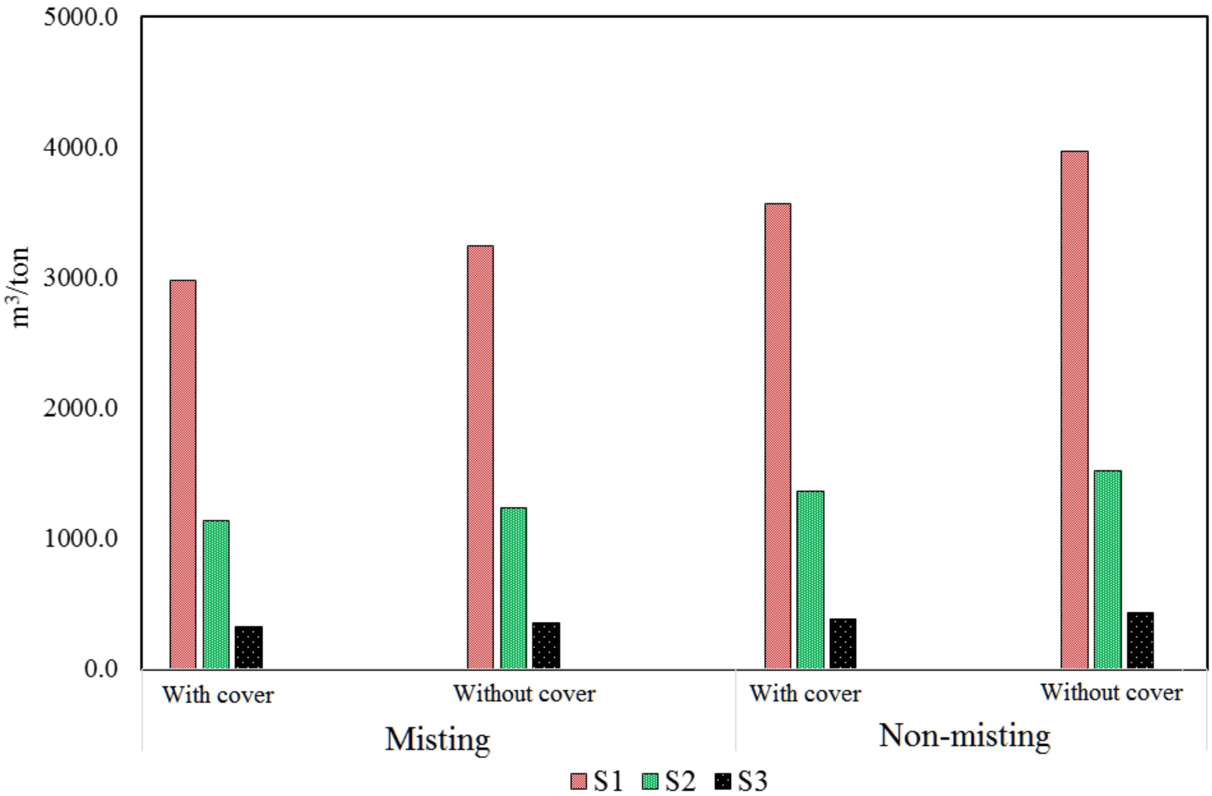

Fig. 2. Total grey water footprint (m^3/ton)

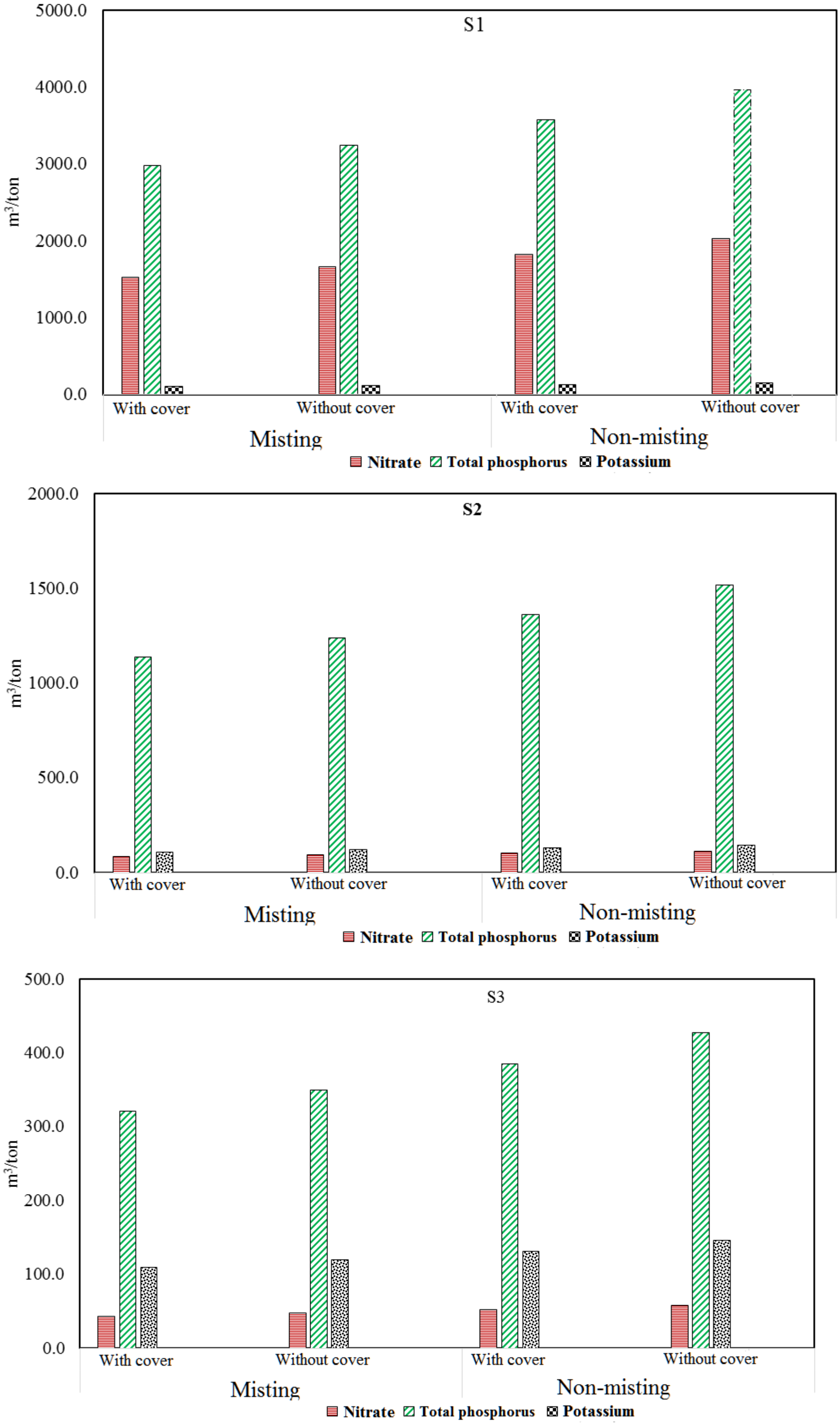

Fig. 3. Grey water footprint (m^3/ton) under different Scenarios (S1, S2, and S3)

3.1. White water footprint

In this study, the water content within the crop per unit area was estimated. The results of this section are presented in Table 3. The water content in the tissue of the bell pepper crop under misting irrigation conditions is higher than under non-misting conditions. This is because the presence of misting increases the relative humidity of the greenhouse, resulting in increased crop productivity and water content in the plant tissue. Additionally, in conditions where pots are covered, the amount of water inside the plant tissue and crop is higher compared to uncovered conditions. This is also due to the increased crop yield under covered pot conditions. On average, under misting irrigation and covered pot conditions, the water content in the plant and crop tissue is 101.21 m^3/ha, under misting irrigation without covered pots, it is 96.03 m^3/ha, under non-misting with covered pots, it is 90.01 m^3/ha, and under non-misting without covered pots, it is 86.13 m^3/ha.

Table 3. Water content in plant tissue and crop (m^3/ha)

		Pot	Water content in plant tissue and crop (m^3/ha)
Misting	With cover	1	100.05
		2	102.66
		3	100.92
	Without cover	4	94.6
		5	96.32
		6	97.18
Non-misting	Without cover	7	89.25
		8	83.3
		9	85.85
	With cover	10	92.02
		11	88.58
		12	89.44

2.3.1. Irrigation water requirements

To calculate the white water footprint resulting from irrigation losses, it is necessary to determine the values of net irrigation requirement and gross irrigation requirement for each of the 12 pots. By measuring daily evapotranspiration, and drainage water from each of the pots, the net and gross irrigation requirements were calculated on a weighted basis throughout the growth period. The results in Table 4 indicate that under conditions of misting irrigation with pot covers, the average net irrigation requirement is 81.4 liter per year (l/year). Similarly, under misting irrigation without pot covers, the average net irrigation requirement is 91.5 l/year. The findings demonstrate that the absence of pot covers can increase the net irrigation requirement by approximately 12%. Moreover, under conditions of non-misting and with pot covers, the average net irrigation requirement is 102.2 l/year, while without pot covers, it rises to an average of 108.5 l/year. A comparison of the results in Table 4 reveals that in the absence of misting irrigation, the net irrigation requirement increases by approximately 18.5% when the pots are uncovered.

Table 4. Net and Gross Irrigation Requirements during the Cultivation Period under Different Experimental Conditions

		Pot	Net Requirement (l/year)	Gross Requirement (l/year)
Misting	With cover	1	80.1	114.5
		2	82.3	117.4
		3	81.5	115.1
	Without cover	4	95.8	129.2
		5	88.6	121.2
		6	90.0	123.3
Non-misting	Without cover	7	110.6	141.0
		8	106.4	136.3
		9	108.5	138.7
	With cover	10	104.0	135.7
		11	100.2	131.4
		12	102.3	133.7

The results from the white water footprint analysis, focusing on irrigation losses, are illustrated in Figure 4. The findings reveal that with misting and pot covers, the white water footprint due to losses is 12.73 m^3/ton. In contrast, with misting but no pot covers, it increases to 13.31 m^3/ton.

In the absence of misting but with pot covers, it rises to 13.68 m^3/ton, and without both misting and pot covers, it reaches 13.94 m^3/ton. These results highlight how misting and the use of pot covers directly impact the reduction of evaporation and transpiration, making them significant factors in water conservation strategies.

Figure 5 indicates that the white water footprint within the plant and crop tissue is highest under the conditions of misting and pot covers, at 0.88 m^3/ton, and lowest under non-misting and no pot covers, at 0.82 m^3/ton. Furthermore, the total white water footprint is 13.61 m^3/ton with misting and pot covers, and 14.18 m^3/ton with misting but no pot covers. In contrast, non-misting with pot covers results in a white water footprint of 14.52 m^3/ton, while non-misting without pot covers leads to a value of 14.76 m^3/ton.

Understanding these components of the white water footprint is essential for effective water resource management in the agricultural sector.

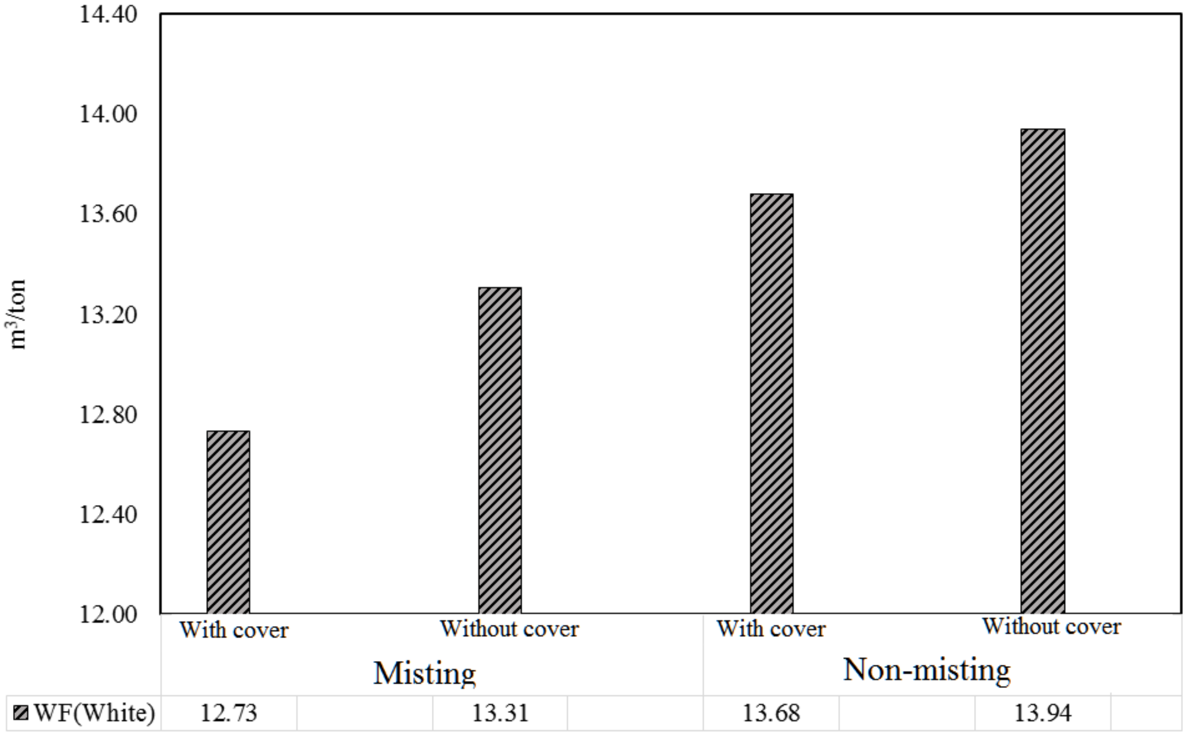

Fig. 4. White water footprint resulting from irrigation losses (m^3/ton)

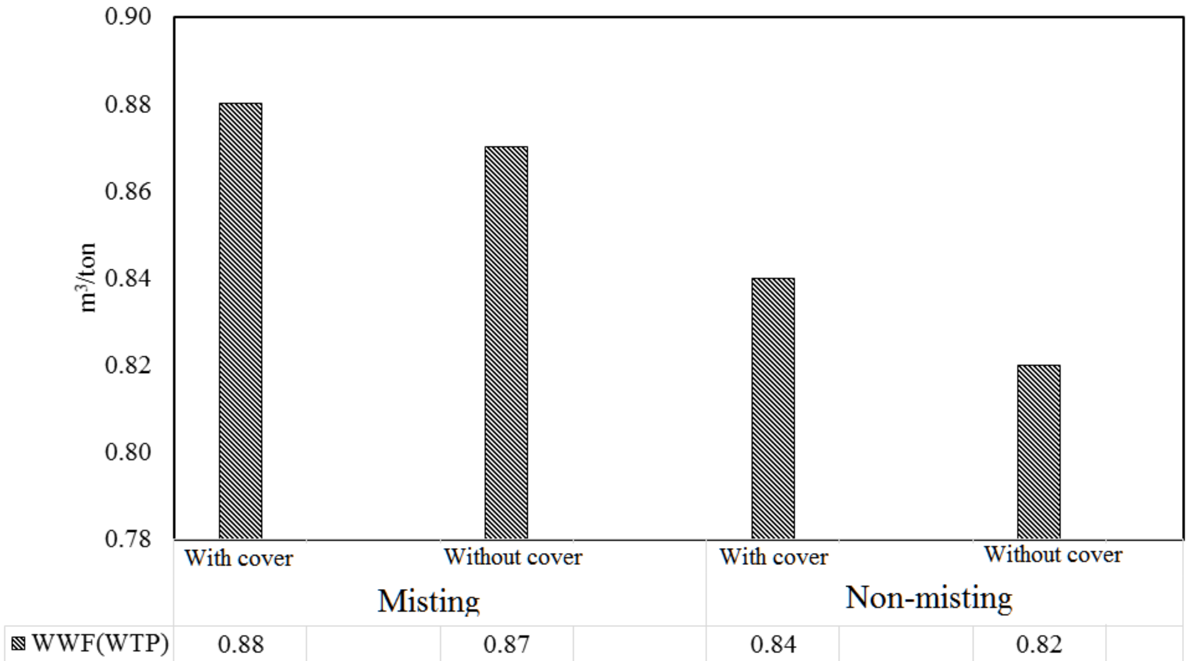

Fig. 5. Whitewater footprint inside plant tissue and product (m^3/ton)

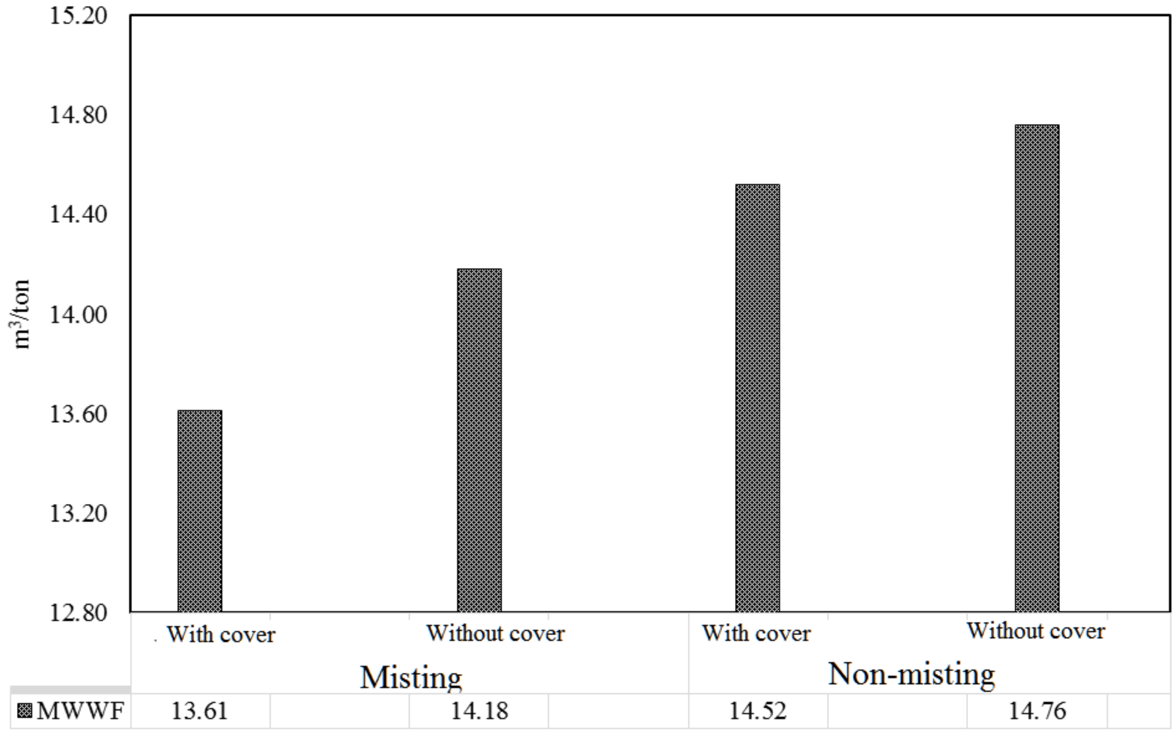

Fig. 6. Total whitewater footprint (m^3/ton)

4. Conclusion

Understanding the concept of water footprint contributes significantly to the management of water resources, especially in the agricultural sector. This study focused on calculating and evaluating the grey and white water footprints of bell pepper under greenhouse conditions. The results demonstrated that water quality standards (C_{max}) have a notable impact on increasing the final grey water footprint. For example, the total grey water footprint of bell pepper under misting and cover conditions was 2976, 1136, and 320.5 m^3/ton for scenarios S1, S2, and S3, respectively. Additionally, under misting conditions, the grey water footprint is lower compared to non-misting conditions. This is because the amount of grey water is indirectly correlated with the crop yield, and since the production of crops is higher under misting conditions, the amount of grey water is consequently lower. Furthermore, covering the surface of pots has a significant impact (9-11%) on reducing the grey water footprint. Moreover, the results indicated that among the three pollutants (nitrate, total phosphorus, and potassium), total phosphorus is critical in all three scenarios S1, S2, and S3. Additionally, the level of grey water footprint can vary under different water quality standards. The results of white water footprint due to irrigation losses showed that misting activity and pot covers have a direct impact on reducing evaporation and transpiration, which is significant. In misting and cover conditions, the total white water footprint is 13.61 m^3/ton, whereas in non-misting and uncovered pot conditions, the total white water footprint is 14.76 m^3/ton. Based on this, it seems that estimating water footprint components in the production process (both in the agricultural and industrial sectors) can be considered as an important part of water resource management studies.

5. Disclosure statement

No potential conflict of interest was reported by the authors

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