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Enhancing Water Management in Jordan: A Fresh Tomato Water Footprint Analysis

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ABSTRACT

Water footprint (WF) analysis is crucial for comprehending agricultural water usage patterns. This study aims to determine the total WF for tomatoes in Jordan from 1994 to 2023, covering both summer and winter seasons, to inform decision-making regarding tomato cultivation practices in the area. Despite inconsistencies in data recording, particularly regarding fertilizer application and sunshine, the WF serves as a valuable tool for estimating seasonal variations in water requirements and facilitating comparisons between different approaches to water usage for tomatoes. Comparative studies globally suggest variability in WFs due to factors such as climate, irrigation methods, and soil conditions influencing results. In this study, the CROPWAT 8.0 model was employed to analyze input data obtained from the Department of Statistics, NASA POWER, and local farmers near the Baqoura, Deir Alla, and Ghour Alsafi stations. The analysis aimed to determine the green WF (rainfall), blue WF (irrigation), and gray WF (water required to dilute pollutants) at these stations. The results revealed that the total WF during winter was approximately 7217.62, 8417.65, and 14061.42 m3/ton for the Baqoura, Deir Alla, and Ghour Alsafi stations. In summer, the respective values were around 3107.67, 6026.52, and 11847.35 m3/ton. Significant findings include ET green, evapotranspiration (ET) blue, crop water use (CWU) green and blue, and production yield for 2023. The nitrogen application per dunum was also calculated as 368 kg/30 dunum, equating to 123 kg/ha. The significance of these results lies in their potential to inform and optimize water management practices in tomato cultivation, promoting sustainability and resource efficiency.

Keywords: Application ratio, blue water footprint, crop coefficient, crop water use, CROPWAT 8.0 model, evapotranspiration, green water footprint, gray water footprint

INTRODUCTION

Water is a fundamental resource for agricultural production and human survival, playing a critical role in safeguarding food security (Rafiei Sardooi et al., 2024). Increased water usage and scarcity have emerged due to various factors, including population growth, socioeconomic advancements, and shifts in consumption patterns (Liu et al., 2017; Shahid et al., 2018; Rafiei Sardooi et al., 2024). Agriculture is both a significant contributor to and a victim of water scarcity (Hoekstra, 2011). Water scarcity not only impacts agricultural practices but also leads to food insecurity as farmers face challenges in accessing dependable water resources and suitable land for cultivation (Rafiei Sardooi et al., 2024).

Jordan's rainfall exhibits significant spatial and temporal variation, with 90% of the country falling within

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the dry to semi-arid category (Salahat and Al-Qinna, 2015). Aridity categorization maps indicate a shift towards lower rainfall means, with the west-middle region becoming moderately arid and the southern and northern-eastern regions becoming super arid. Regional variations range from 75-110 mm in the Badia region to 100-200 mm in the steppes region, while certain parts of the Jordanian Desert receive less than 30 mm annually. Past studies such as those done by Salahat and Al-Qinna showcase fewer rainy days and decreased overall rainfall in Jordan (Salahat and Al-Qinna, 2015). The annual rainfall data from 2010 to 2022 highlights significant variations. Notably, 2015/2016, 2018/2019, and 2019/2020 recorded high rainfall at 9,483, 9,568, and 10,836 MCM, while 2011/2012 and 2020/2021 had lower rainfall at 5,943 and 5,414.6 MCM (DoS, 2022). These fluctuations impact water availability for agriculture and reservoir storage.

The country's expanding population, arid environment, and limited supply of water all have an impact on the sustainability of agriculture (MoE, 2022). Jordan grapples with consequences, particularly in agriculture and industry, due to insufficient rainfall. Modernizing the municipal water supply system could save half of the nation's water consumption while transforming agricultural production might reduce water use fivefold (Beithou et al., 2022). With 196,000 hectares of cropland, 43% irrigated, and 57% rainfed, preserving strategic crops and arable land is crucial for addressing water shortages. Water scarcity challenges water-intensive crops like wheat and barley, impacting food security (DoS, 2022; FAO, 2022). Water scarcity occurs when the water demand exceeds available resources (Van Loon and Van Lanen, 2013; Rafiei Sardooi et al., 2024). The annual renewable water resource of 75 m /person in Jordan is well below the 'absolute water scarcity' threshold (MWI, 2016), placing the country among the lowest in the region in terms of water share per capita. Therefore, it is crucial to enhance agricultural water efficiency and alleviate water stress resulting from agricultural production to ensure the sustainability of water resources (Rafiei Sardooi et al., 2024).

Globally, tomatoes are one of the most widely cultivated and consumed vegetables. They are rich in essential nutrients like vitamins C and K, potassium, and antioxidants. Tomatoes are grown in diverse climates around the world, ranging from temperate regions to tropical areas. Major tomato-producing countries include China, India, the United States, Turkey, and Egypt. In recent years, there has been increasing attention on sustainable tomato production practices, including organic farming methods, water conservation techniques, and reducing post-harvest losses (El-Marsafawy and Mohamed, 2021). Additionally, advancements in technology and breeding have led to the development of high-yielding tomato varieties with improved resistance to pests and diseases. Overall, tomatoes remain a cornerstone of global agriculture, providing essential nutrition and contributing significantly to the economies of producing countries (Leeters and Rikken, 2016). Figure 1 illustrates Jordan's tomato self-sufficiency ratio (SSR) from 2002 to 2020, based on data from the Jordanian Department of Statistics.

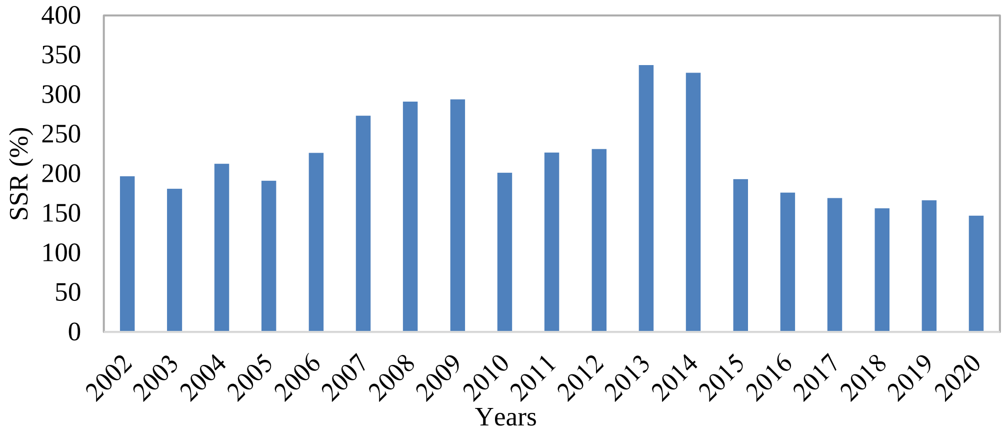

Figure 1: Graph depicting the trends of self-sufficiency in tomatoes in Jordan (2002-2020)(DoS, 2022).

According to Figure 1, the period of (2002 to 2020) saw fluctuations, with a notable increase in SSR from 2008 to 2014. However, subsequent years witnessed a decline in production and exports, leading to decreased SSR and increased tomato imports. Jordan's decreased tomato production between 2014 and 2020 can be attributed to a variety of things such as water scarcity, weather and climate conditions, market conditions, changes in agricultural practices, pest and disease outbreaks, land availability due to urbanization, and socioeconomic factors (Shahid et al., 2018; Rafiei Sardooi et al., 2024).

The data also highlights the significance of tomatoes in Jordan's vegetable exports, constituting 65% in 2015 (DoS, 2022). The tomato sector experienced dynamic trends, with factors like the pandemic contributing to fluctuations in average yield in 2019–2020 (Leeters and Riccen, 2016; DoS, 2022). Figure 2 provides a representation of tomato production in Jordan, highlighting the production trends over the years.

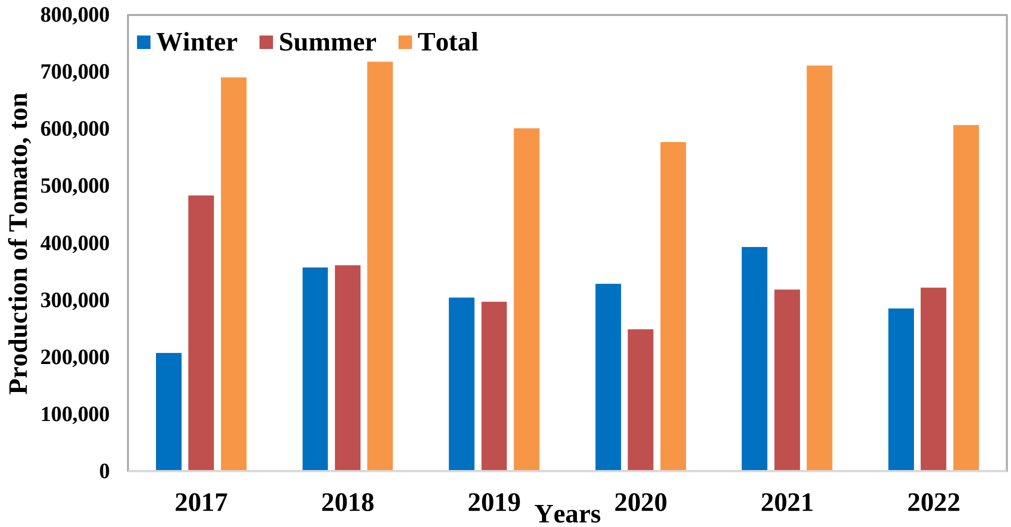

Figure 2: Production of tomato in Jordan (2017-2022) (DOS, 2022).

As shown in Figure 2, in 2017 and 2018, there was a high production of tomatoes, whereas in the subsequent years, the production declined to lower levels. Which explain the variation in tomato production in Jordan from 2017 to 2022. However, tomato production in Jordan exhibits slightly greater variability across both years and seasons. In 2017, there was a notable contrast in tomato output between summer and winter, whereas, in 2018, the disparity between summer and winter production was negligible. This pattern has persisted in recent years, exemplified in 2022, where tomato production remain at approximately 300,000 tons during both summer and winter seasons. As illustrated in Figure 3, the data from 2017 to 2022 focuses on Jordan's tomatoes. It includes average yearly yield in (ton per dunum), total yield in (ton), and cultivated areas in (dunum). The mean annual yield of tomato cultivation ranges approximately from 6 to 9 tons per dunum per year, exhibiting slight fluctuations across consecutive years. The dataset depicts consistent trends with minor variances observed between the summer and winter seasons.

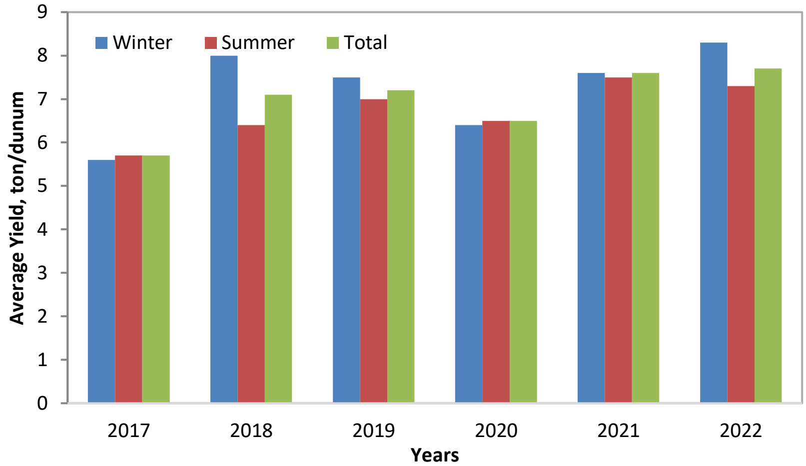

Figure 3: Average yield of tomato production (2017-2022) (DOS, 2022).

Insufficient infrastructure, restricted financial accessibility, and insufficient coordination impede the effectiveness of tomato cultivation inside the nation (Alhammad and Awaideh, 2023). Consequently, during the designated period, all these challenges contributed to a role in the decline in tomato production.

Water Footprint

The water footprint (WF) is a crucial metric for assessing the impact of production on water resources, categorizing water usage into gray, green, and blue footprints. The blue footprint measures freshwater consumption in goods and services production, excluding crop irrigation methods. However, a favorable blue water footprint doesn't universally signify sustainability due to factors like inadequate irrigation resources (Hearth et al., 2014). The green footprint represents changes in soil moisture during agricultural production, emphasizing the reliance on natural rainfall. Finally, the gray footprint quantifies water pollution, considering pollutant loads and adhering to water quality standards. These three footprints collectively offer a comprehensive view of water management practices and environmental impacts, guiding strategies for sustainable water use (Ene and Teodosiu, 2011; Hearth et al., 2014; Ansorge et al., 2022).

The WF is vital for evaluating water quality and overall availability. Integrating water quality in the assessment framework is crucial to quantifying changes in usability (Ansorge et al., 2022). The availability footprint, considering both quantitative and qualitative aspects, determines whether water meets specific needs. Proposing a water quality index aids in assessing consumptive water use and quality exploitation. A comprehensive understanding of the WF and its correlation with water quality is pivotal for sustainable water management (Jia et al., 2019). Some WF methods face criticism for limiting meaningful comparisons among products from regions with varying water-resource availability. Measurement challenges include assessing soil water content, drainage, and nitrate concentrations. To enhance comparisons and address environmental impacts, alternative methods, and increased data collection are needed. Efforts to refine WF measurement techniques are ongoing for accuracy and relevance across diverse contexts (Herath et al., 2014). Certain gray WF calculation methods overlook natural self-purification processes, potentially leading to inaccurate sustainability assessments. Moreover, the gray WF neglects the impact of additional pollutant sources in the river basin, resulting in an actual WF higher than calculated. These limitations highlight the need for improvements in the gray WF methodology, incorporating natural purification processes and considering a broader range of environmental factors for a thorough and precise evaluation of water use sustainability (Ansorge, et al., 2022).

Climate change significantly impacts WF in agriculture, affecting irrigation water availability. Altered rainfall and temperatures may raise water use, impacting crop WF, such as tomatoes. Understanding these patterns and implementing resilient measures necessitates recognizing the climate change-WF link (Maureira et al., 2022). Elevated temperatures increase evaporation, potentially reducing water availability. Temperature and precipitation shifts influence agricultural productivity, a key WF factor. Recognizing the intricate climate change-water resources relationship is vital for comprehending the impacts on footprints and implementing adaptive strategies across sectors (ElFetyany et al., 2021).

The objective of this study is to determine the average WF for tomatoes in Jordan across both summer and winter seasons from 1994 to 2023. To show how international trade and water management practices are related, the concept of virtual water was introduced in the 1990s. It indicates the amount of water used in the production procedure and the transfer of goods, acknowledging that water is used during the process but isn't physically present in the finished product. Water-intensive goods can be imported by countries instead of being produced locally, preserving local water supplies. This idea is crucial for countries that are experiencing water scarcity because it provides information for developing strategic choices about food security laws and the dynamics of agricultural commerce (FAO, 2012).

Review of Literature

The purpose of this analysis of the literature is to investigate the strategies that are frequently used to evaluate the WF of tomatoes in Jordan and worldwide, in comparison to assessments of other crops that are comparable. Furthermore, this review aims to clarify the difficulties and constraints associated with precisely identifying the different elements of tomatoes' WF, with a special emphasis on the grey WF. This investigation is important because it offers a comparative framework for analyzing tomatoes' WFs, which will help farmers make better decisions about their farming methods. We want to determine the current state of tomato WF in Jordan and globally by reviewing the literature and assessing how this information might guide decisions related to agriculture, society, and the environment. The main objective of this study is to advance knowledge about the implications of tomato WF and how they influence sustainable farming methods. The literature search strategy primarily targets studies investigating the WF of various crops, including tomatoes, across different geographic regions. These studies typically delve into the assessment of green, blue, and grey WFs, elucidating methodologies employed, outcomes obtained, data disparities, and methodological challenges encountered during data acquisition. The consensus among researchers underscores challenges inherent in data collection processes, particularly regarding the accuracy of inputs such as sunshine data, fertilizer usage and self-purification processes (Ansorge, et al., 2022), soil characteristics, and agricultural practices (Deepa, et al., 2021). Research endeavors focus on scrutinizing and interpreting green, blue, and grey WFs, utilizing meteorological parameters like humidity, temperature, and precipitation. Notably, emphasis is placed on exploring the WF of tomatoes and its implications for optimal water resource management. Understanding the hydrological ramifications and associated challenges of water inflow and outflow modeling is pivotal in informing decisions regarding sustainable agricultural practices.

The assessment of water footprints across various countries reveals significant disparities in water usage and availability. In Egypt, for the period 2012-2016, the national WF averaged 111.05 billion m^3, surpassing the available water resources of 75.66 billion m^3, resulting in a substantial water deficit. This underscores the urgent need for comprehensive analyses to inform effective water management policies, particularly amidst potential climate change impacts affecting temperature, precipitation patterns, and agricultural productivity (ElFetyany, et al., 2021). Similarly, in Saudi Arabia, the WF of tomato production is significant, with green, blue, and grey WFs totaling 469 m^3/ton, considerably higher than the global averages reported by Water Stat (Multsch, et al., 2013). Meanwhile, in Rhode Island, the average WFs from 2000-2014 indicate varying patterns, with the blue WF notably higher than green and grey footprints, suggesting diverse regional water usage dynamics. These findings underscore the importance of considering geographical and seasonal variations in WFs worldwide, necessitating tailored approaches to sustainable water resource management and agricultural practices across different regions (Symeonidou and Vagiona, 2019).

Research about quantifying and reducing the WF of rain-fed potatoes in New Zealand investigates the WF associated with rain-fed potato production, focusing on quantification and mitigation strategies. Through a combination of field measurements and mechanistic modeling, the study evaluates the blue WF (groundwater use), green WF (soil-water store use), and gray WF (water required to dilute NO_3-N in drainage) of potato cultivation. Results indicate minimal impacts on water quantity, with the green WF, deemed negligible and the blue WF even showing a negative value, suggesting no detrimental effects on water quantity. However, the grey WF, primarily originating from the cropping stage, is identified as a potential concern due to leached NO_3-N concentrations. Various fertilizer application scenarios are modeled, illustrating potential reductions in nitrate concentrations and the grey WF. The study underscores the necessity of considering both water quantity and quality aspects in assessing the WF of agricultural systems. Challenges include the reliance on assumptions and approximations in WF calculations, as well as the difficulty in capturing temporal variability in water and nutrient dynamics influenced by weather conditions. Integrating field measurements with modeling approaches is recommended to improve the accuracy of long-term WF estimations (Hearth, et al., 2014).

In their 2014 research, Hearth et al. aimed to clarify nitrogen dynamics in rain-fed potato production. Findings showed a negative WF Blue, contributing positively to groundwater recharge. Nitrate's impact on water quality showed minimal significance. The study proposed altering fertilizer practices to mitigate nitrate leaching. Meanwhile, Cucek et al. (2012) explored sustainability footprints, defining, and measuring environmental, social, and economic footprints. The research aimed to contribute significantly to sustainability assessment by providing insights into challenges and techniques for accurate measurement and optimization of footprints across social, economic, and environmental dimensions. This study highlights areas for development in long-term strategies for water management while offering insights into the efficiency of water consumption. In-depth knowledge of the WF and an evaluation of the sustainability of resource use are necessary to address the region's broader issues with water scarcity (Hoekstra, et al., 2011).

Additionally, Italian industrial tomato production, with a WF of 114 m^3/t (50% blue, 30% green, and 17% grey), was examined by Aldaya and Hoekstra, (2010). When these results were compared to those of Chapagain and Orr, (2009), the blue component agreed with them, but the grey and green components were much greater in the Italian productive system because of variations in weather and fertilizer inputs.

El-Marsafawy and Mohamed (2021) conducted a comprehensive investigation into the water WF of Egyptian crops, analyzing diverse regions and comparing footprints with the global average. The study included an economic analysis, emphasizing green and blue WF components. Results showed modest green water contribution to Egyptian crop WF compared to blue water. The average total WF was around 680 m^3/ton, deviating from the global average. Economic analysis revealed varying net returns for specific crops, with higher returns for crops like pepper and eggplant. Using the Crop Wat model, the study enhanced understanding of the relationship between water usage and economic returns, emphasizing the need for a comprehensive water footprint evaluation in guiding sustainable water management practices in Egypt's agriculture (El-Marsafawy and Mohamed, 2021).

Mokhtar et al. (2021) explore sustainability footprints, vital indicators spanning environmental, social, and economic dimensions. Their objectives include providing a comprehensive overview, elucidating definitions and measurement units, evaluating composite footprints, and introducing diverse evaluation tools. Footprints quantify sustainability, bridging human activities with environmental, social, and economic consequences. Recognizing definitions and measurement units is crucial for effective assessment methodologies. The review emphasizes the significance of assessing composite footprints to enhance understanding of sustainability challenges. The exploration of tools highlights evolving methodologies for footprint evaluation, contributing nuanced insights to sustainability assessment across dimensions (Mokhtar, Elbeltagi, Maroufpoor, Azad, & He, 2021).

ElFetyany et al., (2021) investigate the sustainability of footprints, integral indicators spanning environmental, social, and economic dimensions. Objectives encompass offering a comprehensive footprint overview, elucidating definitions, assessing composite footprints, and presenting evaluation tools. Footprints quantify sustainability, capturing the interplay between human activities and their consequences. Understanding definitions and units is crucial for effective assessment. The review underscores composite footprint assessment, recognizing its holistic value. The exploration of diverse tools highlights evolving methodologies. Footprints offer a standardized framework to assess and mitigate human impact. This review contributes valuable insights to sustainability assessment, offering a nuanced perspective on measuring footprints across dimensions.

Methods

The primary focus of this study revolves around investigating key indicators, specifically the water footprint associated with tomato cultivation in Jordan. The calculation of the water footprint of crop production in this study adheres to the guidelines outlined in the water footprint assessment manual by Hoekstra et al., (2011) and employs the CROPWAT model. The selection of this methodology is grounded in its widespread adoption as a standalone approach, providing comprehensive volumetric water footprints. This approach considers the three components of water volume (blue, green, and grey), offering valuable insights for effective water resources management.

Data Collection

The climate data required as input for the CROPWAT 8.0 model (FAO, 2024) covering the period from 1994 to 2023 was sourced from NASA POWER. This dataset encompasses measurements obtained from three meteorological stations in Jordan, namely Baqoura, Deir Alla, and Ghour Alsafi. The collected data serves as crucial input for the model to accurately calculate crop water requirements and irrigation needs. Simultaneously, the study incorporates production data obtained from DOS, 2022, for tomatoes illustrating the yield in tons per hectare. This combination of climate and production data forms the foundation for a comprehensive analysis of the WF associated with tomato cultivation in the specified region over the specified timeframe since tomato crop yield is the output from a specific land area or crop, a key metric for productivity.

Typically expressed per unit area, it provides insights into annual production, accounting for variations in growth stages (Duarte, et al., 2014). In assessing a crop's WF, yield is crucial, especially in calculating the grey component. This component considers variables like chemical application rate, leaching runoff, maximum concentration, and pollutant levels (Jia, et al., 2019). Initially, raw climate data (maximum and minimum temperature, relative humidity, wind speed, and sunshine) were converted into monthly averages and further transformed into Microsoft Excel 365. Long-term average climate data for each station were input into the CROPWAT 8.0 model under the "$Climate/ET_0$" icon. Reference evapotranspiration (ET_0) was calculated using the FAO 56 Penman-Monteith method within the software, as presented in Equation (1) (Allen, et al., 1998):

$$\boldsymbol{ET_o} = \frac{\mathbf{0.408}\Delta(\boldsymbol{R_n} - \boldsymbol{G}) + \boldsymbol{\gamma}\frac{\mathbf{900}}{\boldsymbol{T+273}}\boldsymbol{u_2}(\boldsymbol{e_s} - \boldsymbol{e_a})}{\Delta + \boldsymbol{\gamma}(\mathbf{1} + \mathbf{0.34}\boldsymbol{u_2})} \qquad (1)$$

where,

ET_0= reference evapotranspiration, (mm/day).

R_n= net radiation at the crop surface, (MJ/m^2/day).

G = soil heat flux density, (MJ/m^2/day).

γ = psychometric constant, (kPa/ºC).

T = mean daily air temperature at 2 m height, (ºC).

u_2= wind speed at 2 m height, (m/s).

e_s = saturation vapor pressure, (kPa), and e_a = actual vapor pressure, (kPa).

($e_s - e_a$) = saturation vapor pressure deficit, (kPa).

Δ = slope vapor pressure curve, (kPa/ºC).

The estimation of actual crop evapotranspiration (ET_c) is achieved by multiplying the crop coefficient (Kc) with the ET_o. Equation (2) succinctly presents the mathematical representation of the ET_c:

$$\boldsymbol{ET_c} = \boldsymbol{K_c} * \boldsymbol{ET_o} \qquad (2)$$

where,

ET_c = actual crop evapotranspiration, (mm/day).

K_c= crop coefficient.

The K_c values are obtained from the FAO database for tomato crops.

The rainfall data for each station was incorporated into the software under the "Rain" icon within the module bar. This data serves the purpose of calculating effective rainfall (mm), representing the portion of rainfall stored in the soil profile that aids in crop growth. The calculation employs the USDA Soil Conservation Service method, a default option recommended by FAO. The CROPWAT model facilitates the computation of effective rainfall using the USDA Soil Conservation Service. Collected samples for the three stations of the Average Monthly Climate Data during the period (1990-2023), which will be presented in a table showcasing detailed information.

Crops and Crops Parameters

The current investigation is focused on major field crops, with a specific emphasis on tomatoes. The "Crop" module, accessible through the corresponding icon in the module bar, facilitates the selection of crop-related data. Opening the data window defaults to the non-rice crop data type. Kc values for tomatoes were sourced from the FAO database embedded within the CROPWAT 8.0 model.

These Kc values encompass information related to various development stages (initial, development, mid-season, and late season), rooting depth (m), correct depletion (fraction), yield response factor, and crop height (m). The duration of each growth stage, set at 180 days for tomato crops, was obtained from the FAO crop calendar of Jordan. Planting and harvesting dates aligned with the FAO crop calendar of Jordan were also incorporated into the study.

Soil Parameters

Choosing the "Soil" module is done by selecting the respective icon in the module bar. The soil parameters are sourced from the FAO database, considering soil type.

The CROPWAT 8.0 model incorporates comprehensive soil information, encompassing total available soil moisture (mm/m), maximum rain infiltration rate (mm/day), maximum rooting depth (cm), and initial soil moisture depletion (as a percent of total available moisture (% of TAM)) for determining initially available soil moisture (mm/m). As per the findings of Maffia et al., (2023), sandy loam soil and sandy clay soil are identified as optimal for the cultivation of tomato crops.

Crop Water Requirement Option (CWR)

The Crop Water Requirement (CWR) module can be accessed by selecting the "CWR" icon in the module bar, requiring "$Climate/ET_0$", rain, crop, and soil data. Crop water requirement (CWR, mm) represents the necessary water amount for crop growth, influenced by factors like Kc and ET_0, both sensitive to climate variables (temperature, humidity, wind speed, and sunshine). CWR is calculated using equation (2), equivalent to ETc under ideal, unrestricted water conditions, as expressed in equation (3) (Allen, et al., 1998).

$$\boldsymbol{CWR = K_c * ET_o = ET_c} \qquad (\mathbf{3})$$

The Green evapotranspiration ($ETgreen$) is determined by either the effective rain (P_{eff}) or ETc. If $_{eff}$ surpasses ETc, $ETgreen$, equals the ETc, value since crops don't utilize more than ideal growth requires. If P_{eff} is less than ETc, $ETgreen$ becomes the total effective rain. The computation for $ETgreen$ is detailed in equations (4):

$$\boldsymbol{ET_{green}} = \mathbf{min}\ (\boldsymbol{ET_c}, \boldsymbol{P_{eff}}) \qquad (\mathbf{4})$$

The Blue evapotranspiration (ET_{blue}), also termed irrigation requirement (IR), is the disparity between ETc and P_{eff}. When P_{eff} exceeds ETc, ET_{blue} is zero, signifying no need for irrigation. In cases where effective rain doesn't fulfill the entire CWR, ET_{blue} becomes the difference between them. The computation for ET_{blue} is outlined in equations (5):

$$\boldsymbol{ET_{blue}} = \mathbf{max}\ (0, (\boldsymbol{ET_c} - \boldsymbol{P_{eff}})) \qquad (\mathbf{5})$$

To compute the rates of green and blue evapotranspiration (ET), the software provides two options: the crop water requirement option and the crop irrigation schedule option. The Schedule module is accessible through the "Schedule" icon in the module bar, necessitating data on "Climate/ET_0", rainfall, crop, and soil. This module conducts calculations, generating a daily soil water balance. Two scenarios are available:

1. **Rain-fed Condition:** Simulates a scenario without irrigation. Here, ET_{green} equals ET, with ET_{blue} set to zero.

2. **Irrigated Condition:** Simulating irrigated conditions involves specifying the crop's irrigation method. An irrigation method refers to the method utilized to supply water to crops. It determines how water is delivered to the fields to meet the crop's water requirements. The total water evapotranspiration (ET_{α}), which is the combined amount of water lost through evaporation from the soil surface and transpiration from the plants, throughout the growing period, aligns with the term 'actual water use by crop' in the model output. It represents the potential water demand of the crop under ideal conditions, assuming no water limitations.

ET_{blue} equals the minimum of 'total net irrigation' and 'actual irrigation requirement' from the model output. The computation for ET_{blue} is outlined in equations (6):

$$\boldsymbol{ET_{blue}} = \text{min (total net irrigation, actual irrigation requirement)} \qquad (6)$$

ET_{green} equals the ET_{α} minus the ET_{blue} as simulated in the irrigation scenario. The calculation of ET_{green} is demonstrated in equations (7):

$$\boldsymbol{ET_{green}} = \textbf{Actual water used by the crop } (\boldsymbol{ET_a}) - \boldsymbol{ET_{blue}} \qquad (\mathbf{7})$$

Crop Water Use (CWU)

Determining the green and blue components of crop water use (*CWU*) involves obtaining the green and blue evapotranspiration rates specific to the analyzed crop. *CWU* refers to the total water consumption or requirements of a crop during a specific growing season. It encompasses both the green and blue components of evapotranspiration. To determine the green and blue components of *CWU*, specific rates of ET_{green} and ET_{blue} need to be calculated for the analyzed crop. ET_{green} represents the portion of evapotranspiration fulfilled through sources like rainfall and soil moisture, while ET_{blue} represents the portion met by applied irrigation water. By obtaining the crop-specific rates of ET_{green} and ET_{blue}, the total *CWU* can be estimated (Rafiei Sardooi et al., 2024).

The quantity of green crop water used (CWU_{green}, m^3/ha) signifies the volume of rainwater utilized by the crop during evapotranspiration. This is computed by summing the daily green evapotranspiration (ET_{green}, mm/day) across the complete growth duration of the crop and subsequently converting the outcome into water volume in m^3/ha using a factor of 10. The accumulation is conducted by progressing time in 10-day intervals throughout the entire crop growth period, as outlined in equation (8):

$$\boldsymbol{CWU_{green} = 10 \times \sum_{d=1}^{Igp} ET_{green}} \qquad (\mathbf{8})$$

Where *Igp* refers to crop day.

The blue component of (CWU_{blue}, m^3/ha) represents the irrigation water needed for crop growth, encompassing both ground and surface water. The computation of this quantity is elucidated in equation (9).

$$\boldsymbol{CWU_{blue} = 10 \times \sum_{d=1}^{Igp} ET_{blue}} \qquad (\mathbf{9})$$

Water Footprint Calculations

The total footprint (WF_{proc}) of the process of growing tomatoes (crops in general) is the sum of the blue, green, and gray water footprint (equation 10) using the Penman-Monteith equation (Allen, et al., 1998).

$$\boldsymbol{WF = WF_{green} + WF_{blue} + WF_{gray}} \qquad (\mathbf{10})$$

Estimating the green and blue water footprint requires green and blue CWU rates of the studied crop.

1) Green Water Footprint

The WF_{green} is calculated by dividing the green crop water use (CWU, m^3/ha) by the crop yield (Y, ton/ha), as shown in equation (11).

$$\boldsymbol{WF_{green} = \frac{CWU_{green}}{Y}} \qquad (\mathbf{11})$$

Crop yield is obtained from the DOS of tomato crops for the period (1994-2022).

2) Blue Water Footprint

The $\boldsymbol{WF_{blue}}$ is calculated by dividing the $\boldsymbol{CWU_{blue}}$ ($\boldsymbol{m^3}$/ha) by the crop yield (Y, ton/ha), as shown in equation (12).

$$WF_{blue} = \frac{CWU_{blue}}{Y} \qquad (12)$$

3) Gray Water Footprint

The amount of water required to mitigate the concentration of the critical pollutant to permissible levels is deemed adequate to dilute other pollutants. As per the water footprint assessment manual by Hoekstra et al. (2011), equation (13) can be applied to calculate the greywater footprint.

$$\boldsymbol{WF_{grey} = \frac{(\alpha \times AR)/(c_{max} - c_{nat})}{Y}} \qquad (\mathbf{13})$$

Where,

WF_{grey}= grey water footprint, (m^3/ton).

AR = chemical application rate to the field per hectare, (kg/ha).

α = nitrogen leaching-run-off fraction.

c_{max} = maximum acceptable concentration of the pollutant per unit volume of water, (kg/m^3).

c_{nat} = natural concentration for the pollutant considered per unit volume of water, (kg/m^3).

Y = crop yield, (ton/ha).

Results and Discussion

This section provides an in-depth exploration of the study's findings. For clarity, the data gathered for the WF has been organized in tables and depicted graphically across various figures. In light of the data available as of the 1st of February 2023 for the winter season, Table 1 presents information on the WF for tomato production at three different stations in Jordan: Baqoura, Deir Alla, and Ghour Al-Safi. It shows key indicators such as green and blue ET, green and blue CWU, crop yield, and the green, blue, grey, and total WFs. This data helps us understand the water use and environmental implications of tomato production in these areas.

Table 1: Winter station data for rain-fed tomato production in Jordan, Winter 1994-2023 (DoS, 2022).

Station	Winter								
	ET green	ET blue	CWU green	CWU blue	Yield	WF green	WF blue	WF grey	WF Total
	mm/growing period		m^3/ha		ton/ha	m^3/ton			
Baqoura	4.9	719.8	49	7198	1.00415	48.79	7168.25	0.15	7217.19
Deir Alla	3.7	913.7	37	9137	1.09	33.94	8382.57	0.14	8416.65
Ghour Alsafi	3.7	938.4	37	9384	0.67	55.22	14005.97	0.23	14061.42

As shown in Table 1, during the winter, the yield results show variations, with Baqoura, Deir Alla, and Ghour Alsafi stations producing 1.00415, 1.09, and 0.67 tons/ha, respectively. The ET values exhibit differences, with Baqoura at 4.9 mm/growing period, and both Deir Alla and Ghour Alsafi at 3.7 mm/growing period for ET green. Similarly, ET blue varies, with Deir Alla and Ghour Alsafi close at 913.7 and 938.4 mm/growing period, while Baqoura is at 719.8 mm/growing period. CWU for both green and blue is determined by multiplying ET by 10.

The data shown in Table 1 indicates that during the winters from 1994 to 2023, approximately 90% of the tomato production area in Jordan was reliant on rainfall rather than irrigation (DOS, 2022). This aligns with the broader agricultural trends in the country, where around 23% of the total vegetation area is dedicated to tomato cultivation.

According to Table 1, when comparing the WF data for tomato production across the three stations in Jordan, Ghour Al-Safi has the highest total WF at 14061.42 m³/ton, which is significantly higher than Baqoura at 7217.19 m³/ton and Deir Alla at 8416.65 m³/ton. The key driver behind Ghour Al-Safi's elevated WF is its considerably higher WF_{green} of 55.22 m³/ton, as well as a WF_{blue} of 14005.97 m³/ton, both of which are substantially greater than the corresponding values in the other two stations. This indicates that tomato production in Ghour Al-Safi relies more heavily on both rainfall (green) and irrigation (blue) water sources, while also having higher pollution-related water requirements (grey).

In contrast, Deir Alla exhibits the lowest green, blue, and grey WFs among the three stations, resulting in the overall lowest total WF. Baqoura's WF station falls in between those of Ghour Al-Safi and Deir Alla. These distinct variations in WF metrics across the three tomato production regions in Jordan underscore the importance of site-specific factors, such as climate, soil conditions, and agricultural practices, in determining the water use efficiency and environmental impacts of tomato cultivation. Understanding these station-based differences is crucial for developing targeted strategies to enhance the sustainability of tomato production in Jordan's diverse agricultural landscapes.

The WF data for tomato production, which was taken in October for the summer season for the three stations in Jordan, is shown in Table 2. This comparative analysis sheds light on the site-specific water use characteristics and sustainability implications of tomato cultivation in Jordan's diverse agricultural regions.

Table 2: Summer station data tomato production in Jordan, Summer 1994-2023 (DoS, 2022).

Station	**Summer**								
	ET green	ET blue	CWU green	CWU blue	Yield	WF green	WF blue	WF grey	WF Total
	mm/growing period		m^3/ha		ton/ha	m^3/ton			
Baqoura	2.5	510.2	25	5102	1.65	15.15	3092.12	0.09	3107.36
Deir Alla	3.4	647.4	34	6474	1.08	31.48	5994.44	0.14	6026.06
Ghour Alsafi	2.3	661.1	23	6611	0.56	41.07	11805.36	0.27	11846.7

According to Table 2, during the summer, the green WF ranges from 15.15 m^3/ton for Baqoura to 41.07 m^3/ton for Ghour Alsafi, while the WF_{blue} is significantly higher at 3,092.12 m^3/ton for Baqoura, 5,994.44 m^3/ton for Deir Alla, and 11805.36 m^3/ton for Ghour Alsafi. The WF_{blue} notably surpasses both the green and grey WFs, emphasizing the substantial impact of irrigation on the overall WF in these agricultural regions. These findings underscore the critical role of irrigation practices in influencing water consumption patterns and the associated environmental footprint.

The contrast between the blue WF and the combined green and grey WFs is evident in these data across all three stations throughout both the summer and winter seasons. Additionally, the figures reveal that the blue WF at the Ghour Alsafi station is elevated during summer compared to winter, contrary to the expected seasonal pattern where it typically rises during winter.

The grey WF calculation for tomatoes in Jordan involves using Urea as the nitrogen source, with a nitrogen content of 123 kg/ha obtained from the FAO crop calendar. Assuming a 10% leaching fraction, consistent with Hoekstra et al. (2011) for Jordan, this method considers the Jordanian irrigation water quality guideline (2014), specifying a 30 mg/L threshold for nitrogen as nitrate ($N\text{-}NO_3$) and an assumed natural concentration of 10 mg/L. This component, crucial for dilution water, accounts for nitrogen fertilizer use due to its significance as a major pollutant with a high application rate (Hoekstra, et al., 2008), as shown in Table 3.

Table 3: A sample of grey WF calculations of the Baqoura station for 2023 during the winter.

AR	α	c_{max}	c_{nat}	**Yield**	**WF_{gray}**
kg/ha		mg/L		ton/ha	m^3/ton
123	10%	30	10	1.00415	0.615

The application ratio (AR) assessments were tailored to the specific farming practices observed in proximity to the study stations. Farmers in the area traditionally applied 4 bags of 50 kg each, totaling 800 kg of urea fertilizer. The nitrogen content in urea fertilizers is 46%, resulting in 368 kg of nitrogen for the total application (Allen, et al., 1998). Considering the cultivated area of 30 dunum (3 ha), the nitrogen application per dunum was calculated as 368 kg/30 dunum, equating to 123 kg/ha. This nitrogen application rate per hectare is crucial for evaluating potential agricultural risks and optimizing fertilizer management strategies in alignment with local farming practices. The assessment accounts for nitrogen's essential role in crop development and its potential environmental impact, offering insights into sustainable agricultural practices in the study region.

The Department of Statistics only had data on the cultivated area and tomato yields. Consequently, data for the year 2023 about these parameters were directly obtained from field-level farmers, ensuring the accuracy and reliability of the information incorporated into the study, as shown in Table 4. This approach guarantees a more precise representation of on-the-ground agricultural practices, essential for robust scientific analysis and interpretation.

Table 4: Total WF of stations in 2023. Source: Researcher's work.

CROPWAT	WF_{green}	WF_{blue}	WF_{grey}	WF_{total}
	m^3/ton			
Baqoura	15.15	3092.12	0.4	3107.67
Deir Alla	31.48	5994.44	0.6	6026.52
Ghour Alsafi	41.07	11805.36	0.92	11847.35

The comparison between winter and summer seasons reveals intriguing trends in WF dynamics across the studied stations.

As anticipated, Baqoura and Deir Alla stations exhibited higher green, blue, and grey WFs during the winter than in summer, aligning with expectations due to seasonal variations in precipitation and irrigation demand. Conversely, the Ghour Alsafi station presented an unconventional pattern, with the summer green and blue WFs surpassing those of winter, as shown in Figure 4. Consequently, the total WF for Ghour Alsafi was notably higher in summer than in winter, suggesting unique environmental conditions or agricultural practices influencing water usage patterns in this region. These findings underscore the complexity of water resource management and highlight the importance of considering seasonal variations in agricultural WFs for effective policy formulation and resource allocation strategies.

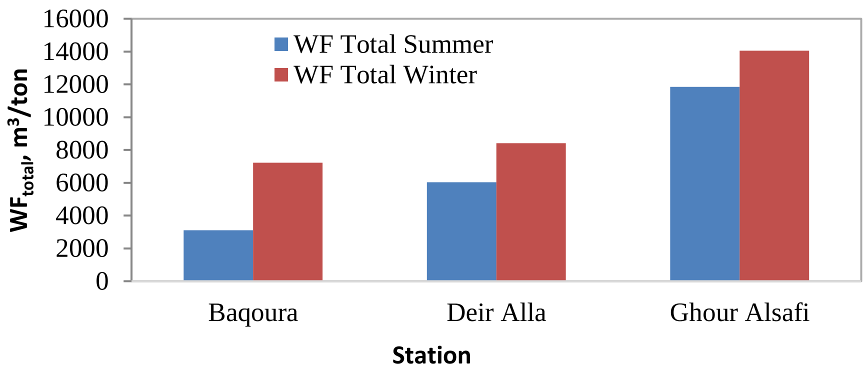

Figure 4: Total WF for all three Stations during both Summer and Winter (1994-2023)

According to Figures 5 and 6, the results reveal notable variations in the green, blue, and grey WFs across the Baqoura, Deir Alla, and Ghour Alsafi stations during both winter and summer seasons. In winter, Baqoura exhibited a green WF of 48.79 m^3/ton, contrasting with 33.94 m^3/ton in Deir Alla and 55.22 m^3/ton in Ghour Alsafi, as illustrated in Figure 5. Similarly, in summer, Deir Alla had the lowest green WF at 31.48 m^3/ton, while Ghour Alsafi recorded the highest at 41.07 m^3/ton, as illustrated in Figure 6. Regarding the blue WF, Ghour Alsafi demonstrated the highest values for both seasons, with 14005.97 m^3/ton in winter and 11847.35 m^3/ton in summer, followed by Deir Alla and Baqoura. The grey WF was notably lower across all stations, with Baqoura displaying the lowest values of 0.15 m^3/ton in winter and 0.4 m^3/ton in summer, followed by Deir Alla and Ghour Alsafi. These findings underscore the variability in WF metrics across different stations and seasons, highlighting the complexity of water resource management in agricultural contexts.

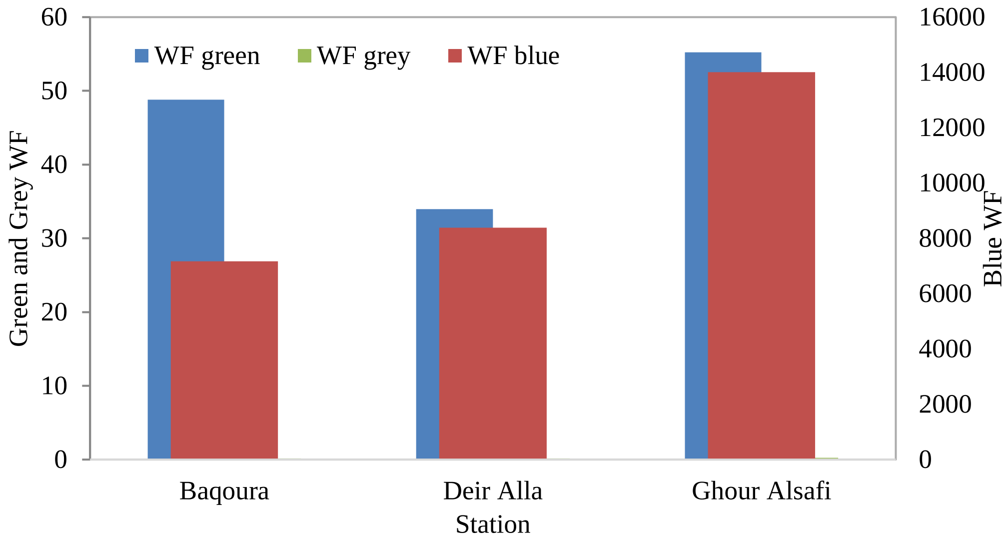

Figure 5: Winter WF (1994-2023).

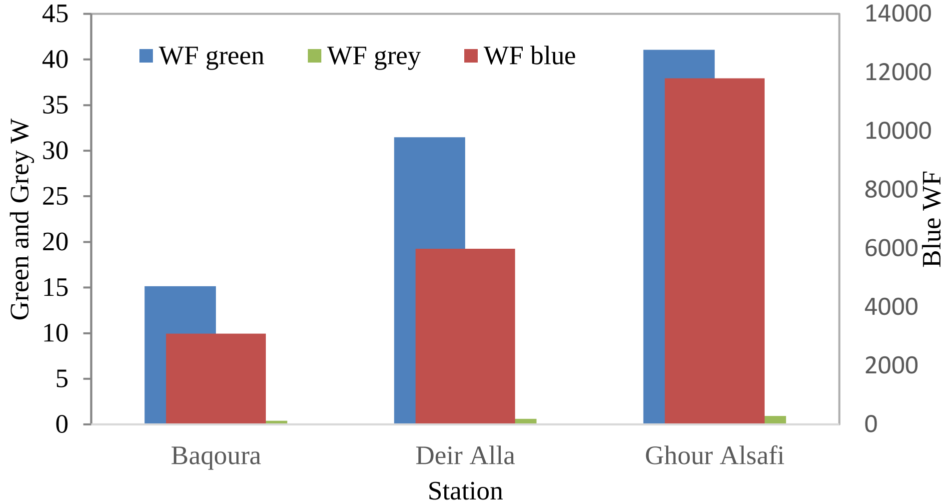

Figure 6: Summer WF (1994-2023).

The discrepancy between WFs for tomatoes in Jordan and the global average raises questions about underlying factors contributing to these variations. The global WF data utilized in this analysis was sourced from a study conducted by Mekonnon and Heikstra, encompassing records solely from the period spanning 1996 to 2005 (Mekonnon and Heikstra, 2011), as illustrated in Figure7.

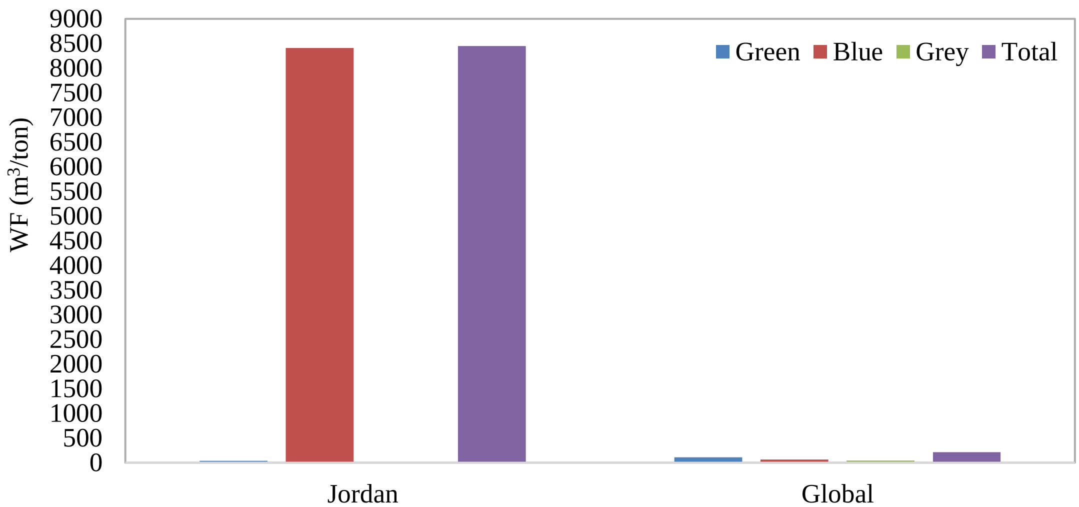

Figure 7: The global and Jordan WFs (Mekonnon and Heikstra, 2011).

As shown in Figure 7, at the WF_{green}, it is evident that Jordan's value of 37.66 m³/ton is significantly lower than the global average of 108 m³/ton. This indicates that the water usage in agriculture within Jordan is more efficient compared to the worldwide standard. However, the WF_{blue} in Jordan, at 8408.11 m³/ton, is considerably higher than the global average of 63 m³/ton. This suggests that the utilization of surface and groundwater resources in Jordan is more intensive. Conversely, the WF_{grey} in Jordan, at around 0.7 m³/ton, is notably lower than the global average of 43 m³/ton, implying that water pollution levels in Jordan are less than the worldwide norm. When examining the total WF, Jordan's value of 8446.482 m³/ton is substantially higher than the global average of 214 m³/ton, indicating that water usage in Jordan, in general, is more intensive compared to the global mean.

The notably lower green WF in Jordan compared to the global average could be attributed to differences in agricultural practices, irrigation methods, and climatic conditions. Similarly, the significantly higher blue WF in Jordan suggests greater reliance on irrigation and possibly less efficient water management practices. The discrepancy in grey WF values may stem from differences in fertilizer usage, soil characteristics, and pollution control measures between Jordan and the global dataset. Exploring recent global WF data on tomatoes could provide further insights into temporal trends and variations, aiding in a more comprehensive understanding of water usage patterns and informing strategies for sustainable agricultural water management.

Conclusion

This study is aimed at elucidating the water demands and associated WF essential for optimizing tomato crop productivity. Furthermore, it endeavors to delineate the seasonal fluctuations in water requirements, based on the results of our study. The WF analysis conducted for tomato cultivation in Jordan from 1994 to 2023 provided valuable insights to inform agricultural water management practices in the region. The study examined the total WF, as well as the green (rainfall), blue (irrigation), and gray (pollutant dilution) components, across three key stations: Baqoura, Deir Alla, and Ghour Alsafi. The results revealed significant variability in total WF, with winter season values ranging from 7,217 to 14,061 m3/ton, and summer season values ranging from 3,108 to 11,847 m3/ton. The Baqoura station consistently exhibited the lowest total WF, while the Ghour Alsafi station recorded the highest. Additionally, the analysis uncovered high nitrogen application rates of 123 kg/ha, which may contribute to intensive water usage and raise concerns about the sustainability of current tomato cultivation practices in Jordan. These findings provide valuable insights that can inform the development of targeted water management policies and initiatives to optimize resource efficiency and promote environmental sustainability in the region's tomato production. The disparity between these values underscores the diverse water management strategies and environmental conditions across different regions and seasons within Jordan.

Acknowledgment

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تعزيز إدارة المياه في الأردن: تحليل بصمة مياه الطماطم الطازجة

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ملخص

يعد تحليل البصمة المائية ((WFأمرًا بالغ الأهمية لفهم أنماط استخدام المياه الزراعية. تهدف هذه الدراسة إلى تحديد إجمالي WF للطماطم في الأردن من عام 1994 إلى 2023، والذي يغطي موسمي الصيف والشتاء، لإرشاد عملية صنع القرار فيما يتعلق بممارسات زراعة الطماطم في المنطقة. على الرغم من التناقضات في تسجيل البيانات، لا سيما فيما يتعلق باستخدام الأسمدة وأشعة الشمس، فإن الصندوق العالمي للمياه يعمل كأداة قيمة لتقدير التغيرات الموسمية في الاحتياجات من المياه وتسهيل المقارنات بين الأساليب المختلفة لاستخدام المياه للطماطم. تشير الدراسات المقارنة على مستوى العالم إلى وجود تباين في WFs بسبب عوامل مثل المناخ وطرق الري وظروف التربة التي تؤثر على النتائج. في هذه الدراسة، تم استخدام نموذج CROPWAT 8.0 لتحليل بيانات المدخلات التي تم الحصول عليها من دائرة الإحصاءات العامة و NASA POWER والمزارعين المحليين بالقرب من محطات الباقورة ودير علا وغور الصافي. ويهدف التحليل إلى تحديد WF الأخضر (الأمطار)، والأزرق (الري)، والرمادي (المياه اللازمة لتخفيف الملوثات) في هذه المحطات. أظهرت النتائج أن إجمالي التدفق خلال فصل الشتاء بلغ حوالي 7217.62، 8417.65، 14061.42 م3/طن لمحطات الباقورة، دير علا، وغور الصافي. وفي الصيف بلغت القيم المعنية حوالي 3107.67 و6026.52 و11847.35 م3/طن. وتشمل النتائج المهمة اللون الأخضر التبخر المركزي ((ET، والأزرق ET، واستخدام مياه المحاصيل ((CWUباللونين الأخضر والأزرق، وإنتاجية الإنتاج لعام 2023. كما تم حساب كمية النيتروجين المستخدمة لكل دونم على أنها 368 كجم/30 دونم، أي ما يعادل 123 كجم/هكتار. وتكمن أهمية هذه النتائج في قدرتها على إعلام وتحسين ممارسات إدارة المياه في زراعة الطماطم، وتعزيز الاستدامة وكفاءة الموارد.

الكلمات الدالة: نسبة التطبيق، البصمة المائية الزرقاء، معامل المحصول، استخدام مياه المحصول، نموذج CROPWAT 8.0، التبخر، البصمة المائية الخضراء، البصمة المائية الرمادية

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