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Assessing the water footprint of tea: Implications on Türkiye's freshwater ecosystems

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ABSTRACT

The relationships between freshwater systems and agriculture are complex, and they intersect in many ways. Human interference with nitrogen and phosphorus cycles has become so intense that may be the effect of nutrient enrichment in freshwaters. Thus, this study aims to assess current (2022) and future (2032) water footprint (WF) of tea production in Türkiye which is one of the major agricultural practices in the country and its effects on freshwater sources. The Water Footprint Network (WFN) suggested methodology for water footprinting was followed during the study. Results showed that rainwater (green water footprint) is the primary water source to grow the tea plant. The green water footprint (WF_{green} =877 m^3/ton) was followed by blue (WF_{blue}=142 m^3/ton) and grey water footprint (WF_{grey}=75 m^3/ton). This clarifies that there is no risk of producing tea in Türkiye in the near future due to the high green water footprint compared to blue and grey. Furthermore, freshwater systems have a low risk of nutrient pollution, as indicated by WF_{grey}. A further study with high-quality data including the amount and type of fertilizer used is therefore suggested.

Keywords: Agriculture, Freshwater, Tea cultivation, Water footprint, Water resource

Introduction

Life is dependent on water as a vital resource, maintaining ecological health and fostering socio-economic development (Barbosa & Cansino, 2022; D'Ambrosio et al., 2020). There are many pressures on water resources such as increasing population, uncontrolled discharges, excess water abstraction, global warming and climate change (D'Ambrosio et al., 2020). The increase in population triggers greater demand for food, thereby raising trade actions and escalating rivalry between sectors for water resources (Feng et al., 2023). Agriculture stands out as the primary sector using the largest portion of freshwater resources for irrigation and contributing to environmental degradation through diffuse pollution such as pesticides, fertilizers, etc. Humanity's pursuit of sustainability is significantly hindered by intense agricultural activities. Ensuring the preservation of both the amount and standards of water resources and setting a strategy for sustainable water management, it is pivotal to assess the sustainability of human activities (D'Ambrosio et al., 2020). To evaluate water use, Hoekstra & Hung (2002) have established the water footprint (WF) concept determining the use of total water resources including direct and indirect water consumption of producers or consumers. The water footprint has three components, which are green, blue, and grey water. The use of drinking water, irrigation water, and industrial water can be viewed as a blue water footprint. The green water footprint is the total volume of rainwater required to make a product. Grey water footprint refers to the amount of freshwater needed to absorb pollutants to ensure water quality meets standards (Hoekstra et al., 2011).

The leaves of the *Camellia sinensis* plant are the main source of tea and with significant historical, economic, and cultural significance tea is a commonly consumed drink in the world (Hu et al., 2019). Over the past decade, global tea production (including black, green, and others) has risen by an average of 3.2% annually, reaching 6.7 million tons in 2022. This growth has been predominantly by expansion in China, where production has surged by 5.9% annually, escalating from 1.92 million tons in 2013 to 3.34 million tons in 2022 (FAO, 2024). In the past ten years, global tea consumption has been rising at a rate of 3.3% annually, reaching 6.5 million tons in 2022. This increase has been driven by the swift growth in per capita income levels, particularly in China, India, and other Asian and emerging economies (FAO, 2024). Türkiye ranks as the fifth largest tea producer globally (Ozbayram, 2020). While the fresh tea crop yield varied between 1250 and 1400 tons on average in the last four years, the yield increased to over 1355 tons in 2023. In 2023, 1355 tons of fresh tea were processed yielding 270 thousand tons of dry tea (RTB, 2024). Under suitable climatic and soil conditions with effective management, the harvested leaf yield of tea can usually reach 4-5 t ha/year and could be higher (Hajiboland, 2017). Tea production is limited to 6-8 months in countries with relatively high latitudes, such as Türkiye, while tea cultivation is conducted for 12 months in tropical and equatorial regions.

The growing environmental awareness prompts people to inquire more frequently about the hidden natural resources within a product, especially water. This includes the water required for plant growth as well as the water needed to process the crop into its final form (Chapagain & Hoekstra, 2007). The annual freshwater consumption is around 54 x 10^9 m^3 (Altınbilek and Hatipoğlu, 2020) and Türkiye's total water footprint is dominated by the agricultural sector, which accounts for 74%. The majority of water usage in agriculture is used for crop production, with only 8% allocated for livestock grazing. Türkiye is considered to be a water-stressed country, with a water supply availability per person below 1500 m^3. This value will be reduced to 1120 m^3, which is lower than the average global water footprint of 1240 m^3 as the population of Türkiye is expected to reach 100 million by 2040 (Harmancioglu, 2020; Mekonnen and Hoekstra, 2011). Model projections indicate that water potentials in Türkiye will decrease by 16% and 27% by 2050 and 2075, respectively.

Effective water resource management requires the assessment of freshwater water contamination. The eutrophication of surface waters has become a worldwide problem with no end in sight. Biogeochemical flows, which include the nitrogen (N) and phosphorus (P) cycles, are going beyond the planetary boundaries (PBs) (Rockström et al., 2013). The phosphorus reserves will be depleted in less than 200 years (Schlesinger, 2009). Nitrogen fertilizer put on agricultural soils is transported through the environment, polluting water ecosystems, aquifers, rivers, and oceans and harming human health (Baldock et al., 2023). The degradation of freshwater, estuarine, and marine ecosystems is widespread, but it is our freshwaters that are most at risk due to their widespread use (Withers, et al., 2014). Staying within local or global freshwater boundaries can be achieved by diminishing water demand and increasing water use efficiency, which includes the choosing products that require less water and sustainable agriculture practices. Previous studies in the literature have calculated the water footprint of different crops in Türkiye (Muratoglu and Avanoz., 2021; Mekonnen MM, Hoekstra AY 2011) and tea production in various parts of the world (Jefferies et al. 2012 A.K.; Chapagain and A.Y. Hoekstra., 2003). However, they have not focused on the risk of nutrient pollution in freshwater systems due to crop production patterns.

The objective of this study is to evaluate the current (2022) and future (2032) water footprint of tea production in Türkiye and its effect on freshwater resources.

Materials and Methods

Study Area

The analysis of tea cultivation regions in Türkiye indicates that Rize holds the highest share at 74.9%, followed by Trabzon at 13.2%, Artvin at 8.9%, Giresun at 2.3%, and Ordu at 0.6% (Figure 1).

Calculation method and equations of Green and Blue Water Footprints

The present study was carried out in accordance with the Water Footprint Network (WFN) proposed Water footprint methodology (Hoekstra et al., 2011). Tea production, statistics on the climate data and soil parameters in Türkiye were used to calculate water footprint or crop water use CWU (m^3/yr) (Figure 2).

When producing a particular crop, the total water usage is known as CWU (m^3/yr). Measuring or estimation of evapotranspiration and irrigation amounts is required to accurately estimate CWU. Evapotranspiration is the process of water being transferred from the soil surface (evaporation) and plants (transpiration) to the atmosphere. According to the CWR model, the crop's blue water needs (irrigation) is zero if effective rainfall exceeds the total crop evapotranspiration. The blue water requirement is a term that defines how much water is required between crop evapotranspiration and effective rainfall. The water footprint of a product consists of the sum of freshwater utilized to produce the product, calculated across the various stages of the production chain. Water footprint has been calculated according to Hoekstra et al. (2011) in the Eqs. (1) – (2):

$$WFgreen = \frac{CWUgreen}{Yield} \quad (1)$$

$$WFblue = \frac{CWUblue}{Yield} \quad (2)$$

The green water requirement corresponds to the portion of the plant's water needs that is fulfilled by effective rainfall. When the effective precipitation (P_e) exceeds or matches the plant's water consumption, the green water footprint is equal to the plant's water consumption. Green and blue water footprint components of plant water consumption on a geographical basis (m^3/ ha) are values based on the sum of the daily plant water need/evapotranspiration (ET, mm / day) amounts of the plant in the growing season. The green water consumption of the plant represents the amount of rainwater lost from the plant through evapotranspiration during the growing season. Blue water consumption is the sum of irrigation water lost due to evapotranspiration Eqs. (3) - (5):

$$ETblue = \{ETc - Peff \; ; \; ETc > Peff \; 0; \; ETc < Peff \quad (3)$$

$$ETgreen = \{Peff \; ; ETc > Peff \;\; ETc; ETc < Peff \quad (4)$$

$$Peff = \{\frac{P(125-0.2P)}{125}; P \leq \; 250\,mm \; 125 + 0.1P; P > \; 250\,mm \quad (5)$$

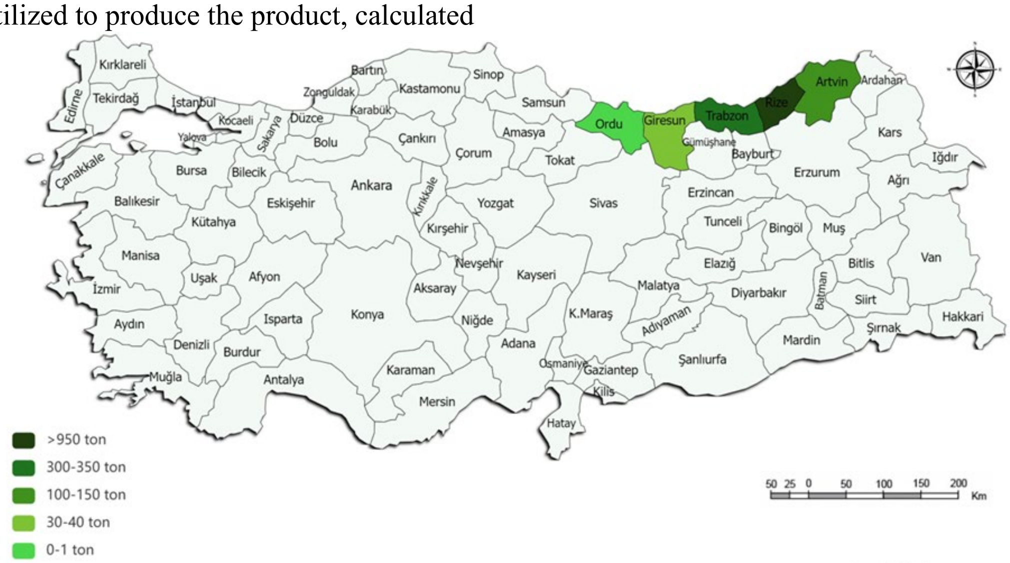

Figure 1. Tea production in Türkiye (thousand tons per year for each province) (TSI)

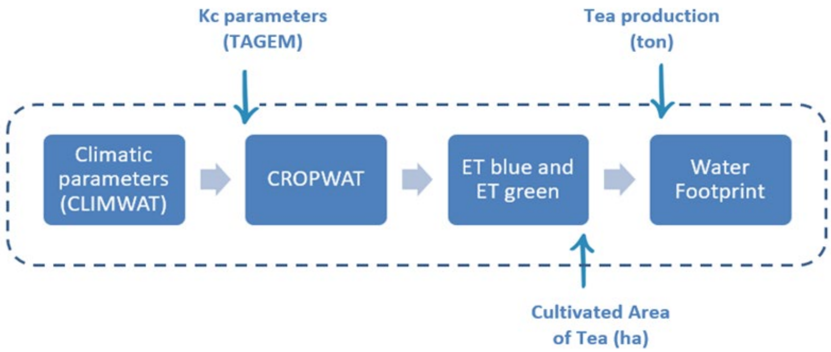

Figure 2. Calculation method of green and blue water footprints (WFN)

Data Inventory and Software

CLIMWAT and CROPWAT software were used for calculations involving blue water and green water. The publication CLIMWAT 2.0 for CROPWAT is jointly produced by FAO's Water Development and Management Unit and Climate Change and Bioenergy Unit. CLIMWAT 2.0 has a comprehensive climatic database that covers more than 5,000 stations worldwide (FAO, 1999a). CROPWAT 8.0 is a tool that can assess farmers' irrigation activities and assessing crop performance in both rainfed and irrigated situations (FAO, 1999b). In this study, the actual amount of irrigation water used in all tea was regarded as equivalent to the irrigation water need calculated by the CROPWAT model.

The ET_0 data used to calculate crop evapotranspiration was derived from long period averaged weather data including the temperatures, humidity, wind speed, solar radiation, and sunshine hours for a given day are listed as daily minimum, average, and maximum temperatures, relative humidity, wind speed, solar radiation, and sunshine hours (Table 1-2).

Table 1. Climate data (CLIMWAT)

	Artvin	Giresun	Ordu	Rize	Trabzon
	Annual Average				
Min Temp (°C)	7.7	11.5	10.6	11.2	10.8
Max Temp (°C)	16.9	17.9	18.6	17.9	17.8
Humidity (%)	65	74	73	80	77
Wind (km/day)	91	73	132	45	104
Sun (hours)	6	5.5	5.9	3.3	3.8
Rad (MJ/m²/day)	13.9	13.5	13.9	10.8	11.5
ET_0 (mm/day)	**2.28**	**2.18**	**2.44**	**1.78**	**2.03**

Table 2. Effective rainfall (CLIMWAT)

	Artvin	Giresun	Ordu	Rize	Trabzon
	Eff rain (mm)				
January	65.2	97.9	81.9	143.4	62.9
February	59.8	76.5	67.5	124.2	48.5
March	51	76.3	66	111.9	50.2
April	55	70.5	60.6	85.4	51
May	48.5	59	46.8	86.7	47.7
June	45.2	68.3	65.2	100	47.7
July	23.1	66	62.2	105.3	32.2
August	25.8	77	59.8	130.6	40.9
September	32.2	92.4	66	143.4	62.2
October	51.8	118.8	100.6	152.2	90.6
November	66	110.1	95.7	150	78.5
December	84	103.7	98.8	147.4	72.7
Total	**607.6**	**1016.6**	**871.2**	**1480.5**	**685**

The purpose of CROPWAT software is to estimate crop water and irrigation needs of various plants using plant patterns, soil, and climate data. The Penman-Monteith method was used (CROPWAT 8.0 model) to calculate reference plant water consumption (ET_0) utilizing daily, 10-day, or monthly climate data Eq. (7):

$$ETo = \frac{0.408\Delta(Rn-G)+\gamma 900T+273u2(es-ea)\Delta}{\gamma(1+0.34u2)} \quad (7)$$

Estimating actual evapotranspiration is vital not only for the study of climate change but also for calculating crop water needs. ET_0 is the standard measure of evapotranspiration, R_n is the the crop surface's net radiation, the density of soil heat flow is G, T is the mean daily air temperature at 2 m height, u2 is the wind speed at 2 m, Δ represents the gradient of the saturation vapour pressure curve e_s is the saturation vapour pressure, e_a is the actual vapour pressure, $(e_s – e_a)$ is the variance in vapor pressure , and γ is the psychrometric constant. Crop evapotranspiration (ET_C) is given in Eq. (8):

$$ET_C = K_C x ET_0 \quad (8)$$

ET_0 and crop coefficients (K_c) are the primary factors that affect water footprint, with blue water footprint being more sensitive than green water footprint (Zhou et al., 2014). The K_C is the crop coefficient for a particular crop and is typically determined by experimentation (Table 3).

Table 3. Tea coefficients (Kc) (TAGEM, 2017)

	Artvin	Giresun	Ordu	Rize	Trabzon
Kc-int	0.8	1	0.88	1.06	0.82
Kc-med	0.95	0.91	0.93	0.91	0.94
Kc-end	0.95	0.92	0.94	0.92	0.96

Turkish Statistical Institute (TSI) database was used to determine the provinces that produced tea in Türkiye in 2018 and 2022 in the study (Table 4). Then, based on the current regional information (tea production amount, precipitation data obtained from climate stations, irrigated cultivation area) for 2018 and 2022, covering the provinces in question, the blue water footprint (irrigation water) and green water footprint (rainfall) of tea production were determined. The only alteration made in 2032 was the quantity of tea production. The current global market situation and medium-term prospects indicate that tea production will increase by 2.4% in 2032 (FAO, 2024). The climatic conditions were assumed to be the same as those in 2022 for the CROPWAT software.

Grey Water Footprint

The greywater footprint calculations were determined by using general approximations and assumptions due to fertilizer application yields, leaching fractions, and maximum permissible concentrations of pollutants that are not point sources (A. Chapagain & Hoekstra, 2003; Yi et al., 2024). Nitrogen and phosphorus leaching have a significant impact on gray water footprints. Previous research that did not include pesticides underestimated the impact of crops on grey water footprints. Therefore, greywater was calculated using literature data that uses N, P, and various pesticide combinations for over a dozen major crops (including tea) in Chinese provinces (Yi et al., 2024) Eq. (9). Freshwater bodies were assumed to have a maximum acceptable concentration of 10 mg N/L and 0.2 mg P/L. The fertilizer N application of 2353 (kg N/ha) and the fertilizer P application of 23 (kg P_2O_5/ha) were assumed for tea. 0.1 mg N/L and 0.01 mg P/L were established as natural concentrations, while pesticides were set to zero. The leaching and runoff fractions for pesticides have been established at 0.001 (α_{min}) and 0.1 (α_{max}) respectively (Franke et al., 2013).

$$WFgrey = \frac{(\alpha \ x \ AR)/(Cmax-Cnat)}{Yield} \quad (9)$$

AR; Chemical implementation amount (kg/ha), α- fraction of leaching runoff, C_{max}-maximum permissible concentrations (kg/m^3), C_{nat}–natural concentration for the pollutant (kg/m^3), Y is the crop yield rate (ton/ha).

Table 4. Tea production, import and export (ton) (Türkiye, TSI)

Year	Fresh Tea (ton)	Import (ton)	Export(ton)	Hectare
2018	1,480,534	94,000	13,000	78,133
2019	1,407,448	59,000	17,000	78,569
2020	1,450,556	74,000	18,000	78,681
2021	1,453,964	101,000	23,000	78,900
2022	1,269,546	55,000	28,000	79,129
2032	1,300,015	56,320	28,672	79,129

* Water footprint calculations included the exported tea product that was produced using the country's water resources.

Results and Discussion

Water Footprint of Tea Production in Türkiye

The objective of calculating the water footprint geographically is to provide information on the potential of certain agricultural production practices to reduce water scarcity and improve water quality. These can be listed as plant characteristics, climate, plant growing plan (number of days grown), environmental variables such as soil properties, agricultural management practices and human impact such as irrigation.

The amount of water required to make a single unit of tea is known as the virtual water content of tea. Typically, the calculation and representation of tea is done in cubic meters of water per ton of tea. Agricultural water resource allocation varies between production and consumption perspectives in different regions due to differences in crop types, production capacities, and water needs. Trading virtual water between provinces is a key method for balancing the disparities between food production and consumption, and it significantly influences the agricultural water footprint (Cao et al., 2023). The tea produced in Türkiye is consumed extensively by its population. The water footprint of production (1.6 x 10^9 m^3/year) is significantly higher than that of exports (3.5 x 10^7 m^3/year) and imports (6.9 x 10^7 m^3/year) for this reason (Figure 3). Import and export water footprints were calculated solely on the amount of tea, and the effects of transportation and storage during the supply chain were not taken into account. Including these processes will result in higher values, but they will still be very low in comparison to the production water footprint.

Research on water usage in comparable products is limited. However, existing studies have varied in their scope. For instance, Chapagain and Hoekstra concentrated on water consumption during the agricultural phase and extended their scope to to encompass packaging and the consumer phase. In the Netherlands, coffee and tea consumption has beneficial effects on the economies of the producing countries. Developing countries, which are mostly producing countries, benefit economically from the utilization of a resource (rainwater) that has a reduced opportunity price relative to groundwater and surface water. The financial value of rainwater could be taken into account in the product price, even though it may not have a higher economic return when used for coffee or tea production. (Chapagain & Hoekstra, 2007).

Due to inter-regional virtual water flows, water scarcity can become more severe in crop-exporting regions while easing in crop-importing regions. A study carried out by Jefferies et al. 2012 showed that green water footprint of fresh tea was in the range of 880- 2214 m^3/tons. In a previous study, the virtual water of fresh tea in Türkiye was determined as 1828 m^3/ton for the period 1995–1999 (Chapagain & Hoekstra, 2007). According to Muratoglu and Avanoz (2021) tea production in Türkiye has a water footprint of 526 m^3/ton, which excludes grey water footprint. The total water footprint amount was found as 1094 m^3/ton in this study. While green water composed 80% (WF_{green} =877 m^3/ton) of the water content, the blue water and grey share were around 13% (WF_{green} =142 m^3/ton) and 7% (WF_{green} =75 m^3/ton) between 2018 and 2022. The results reveal that green water accounted for the greater share of fresh tea production in Türkiye.

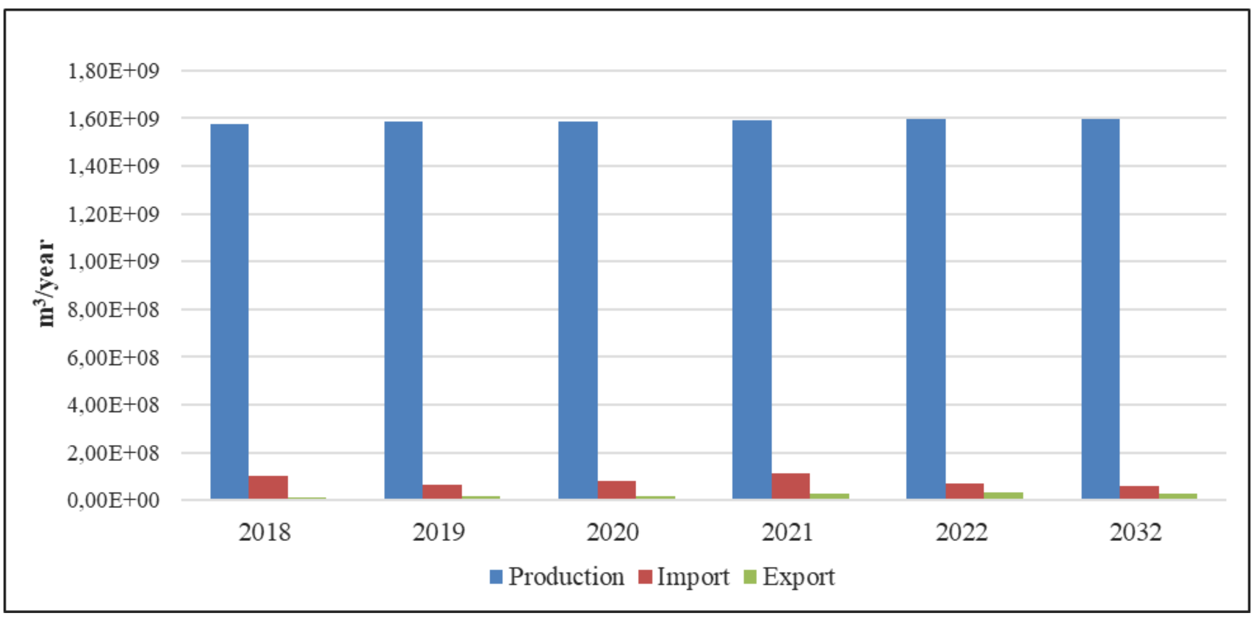

Figure 3. Water footprint **tea** by activities -Türkiye (m^3)

Green water is crucial in the water cycle and is essential for the production of rain-fed crops (D'Ambrosio et al., 2020). Crop cultivation relies more on green water from rainfall than on blue water from irrigation systems (Cao et al., 2023). Since tea is predominantly cultivated under rain-fed mono-cropping systems, weather conditions are crucial for optimal growth which makes it highly vulnerable to climate change, especially global warming. However, in 2032, the calculations revealed a slight difference between green and blue water in tea production. Total green, blue and grey water footprint were determined as 1.28 x 10^9 m^3/year, 2.06 x 10^8 m^3/year and 1.10 x 10^8 m^3/year in 2022 (Figure 4). There won't be any significant changes to the water footprint in 2032.

Implications on Türkiye's Freshwater Ecosystems

Developing water resources at a national scale requires integrated strategies to balance demand and available water, while also considering the declining trend in water availability. The use of irrigated agriculture in developing countries, where water extraction is often unregulated, puts more pressure on available freshwater resources (Sikka et al., 2022). Irrigated areas will increase in the future and more freshwater will be diverted from agriculture. The use of fertilizers in agricultural practice today is characterized by their misuse (Chartzoulakis & Bertaki, 2015). Water bodies have higher loads of nitrogen, phosphorus, and pesticides due to reduced water stream flows. This results in a change in the state of water quality, which means an increase in the concentration of pollutants in water ecosystems (Evans et al., 2019). The contamination of nitrogen and phosphorus by tea production, particularly in regions with intensive cultivation, can have a significant impact on freshwater systems.

Nitrogen and phosphorus are essential for the survival of life. However, they are being absorbed beyond their capacity. The world consumes twice as much nitrogen fertilizer as it requires, and the shortage of phosphorus is increasing at the same time (Helmholtz Centre for Environmental Research, 2022). Improving the chemical and ecological quality of numerous waterbodies impacted by farming remains a challenge for mitigating nutrient loadings from agriculture due to their diffuse nature (Withers et al., 2014). This could be a result of the inadequacy of controls on nutrient transfers from agricultural fields. The excessive use of nitrogen fertilizers results in nitrogen leaching, soil acidification, and runoff, while phosphorus fertilizers cause surface runoff and soil erosion. These pollutants also cause eutrophication, which results in excessive algae growth, oxygen depletion, and loss of biodiversity in aquatic ecosystems. The presence of phosphorus in environments leads to severe algal blooms, which can almost prevent freshwater sources from functioning. The growth of beneficial aquatic plants could be eliminated as a result of algal blooms reducing sunlight to freshwaters, particularly still waters such as lakes. Even without algal blooms, nutrient enrichment from nitrogen compounds can lead to problems such as blue baby syndrome at certain concentrations (Ohio EPA, 2011). To mitigate these effects, sustainable fertilizer practices, buffer zones, and improved soil management can be implemented to reduce nutrient runoff and leaching. Sustainable agriculture can be promoted, and the tea industry's environmental impact can be minimized by adopting these measures. In addition, water quality standards (including limit values for nitrogen and phosphorus) have been developed to protect not only human health but also freshwater sources and marine systems (Liu et al., 2017).

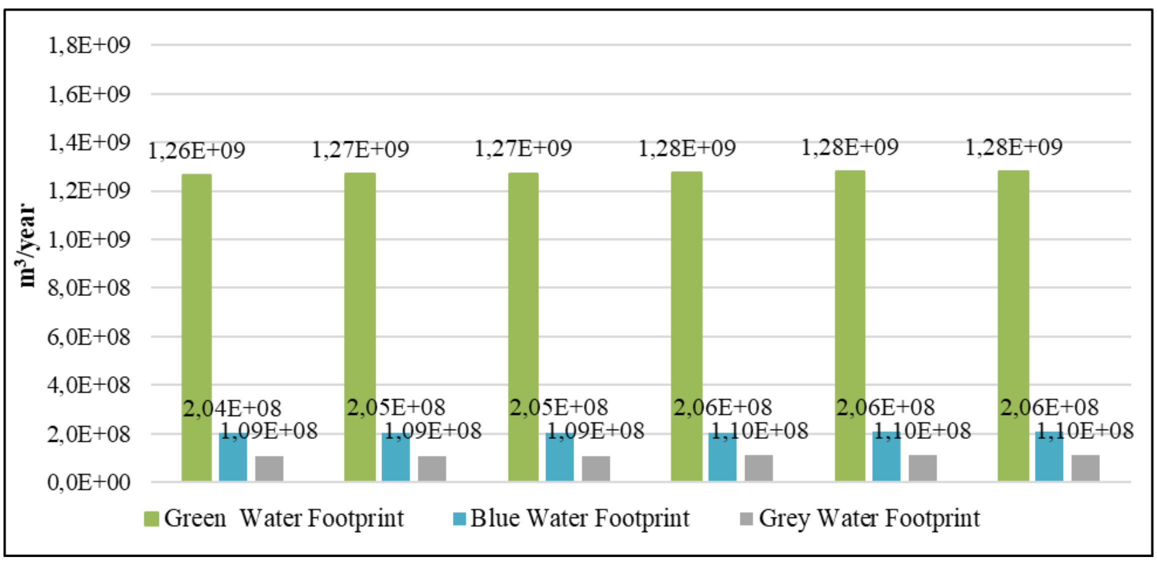

Figure 4. Total water footprint **tea** -Türkiye (m^3)

The majority of nitrogen and phosphorus contamination in Turkish freshwater sources comes from agricultural runoff, industrial discharges, and urbanization. Freshwater systems can be greatly affected by nitrogen and phosphorus pollution caused by tea production, especially in areas with intensive farming. Tea production has a water footprint of 1.6 x 10^9 m^3/year, which is equivalent to 3% of the country's total annual freshwater consumption in Türkiye. Water supply availability in Türkiye is projected to decrease according to models, while tea production patterns will increase. However, low WF_{grey} results compared to blue and green clarify that there is no risk of producing tea in Türkiye in the near future. Freshwater systems are less prone to being polluted with nutrients due to tea production.

Limitations of the Study

This research contributes to the existing literature by calculating the water footprint of tea production and its relations with freshwater resources. However, there are still some limitations, even though a detailed assessment has been conducted. Firstly, monthly data were used for modelling, but detailed reports on evapotranspiration, crop coefficients, and other meteorological variables on a daily basis will be more related in future studies (Nana et al., 2014). Secondly, the annual variations of WF_{grey} are mainly investigated using detailed temporal data of actual fertilizer application by farmers and runoff leaches. Due to the absence of necessary data, WF_{grey} was accepted as the constant throughout the year. Finally, WF_{grey} was calculated using maximum acceptable concentrations of 10 mg N/L and 0.2 mg P/L in freshwater bodies (Yi et al., 2024). Since, grey water calculation is based on the required water for assimilating the pollutants, to bring water pollution in the same unit as a consumptive use, the results of WF_{grey} will differ if a stricter water quality standard is implemented. For instance, these results are complied with Class II: water with low contamination, quality criteria of inland waters in Türkiye but not with Class I: high quality water.

Conclusion

The increasing water scarcity is becoming a more pressing issue, resulting in a shift towards more sustainable systems. The key to creating strategies for saving freshwater resources lies in developing robust results that estimate the future environmental impacts of nations' consumption. Türkiye is a country that is experiencing high water stress. Thus, the county has to manage its finite water resources effectively while protecting the environment and maintaining water quality. By changing local cropping patterns and altering global trade, significant amounts of water can be conserved. Türkiye's water consumption is mainly due to production, not exporting and/or importing. The production stage should be the priority rather than the trade. Thus, the good agricultural practices should be implemented in the field such as adoption of innovative irrigation techniques, using marginal waters (e.g. treated wastewater), optimizing water pricing policy. By providing information to local authorities about rainwater, irrigation, and freshwater usage, this study is expected to make an impact on agricultural water management studies.

Türkiye's tea production has a total water footprint of 1094 m^3/ton, whereas the grey water footprint only covers 75 m^3/ton, as revealed by this study. Grey water footprint results indicate that tea production for freshwaters in Türkiye will not be risky in the near future. However, a further study with high-quality data including the amount and type of fertilizer used will clarify how the freshwater systems effected by the risk of nutrient pollution coming from tea production. The impact of transportation and storage in the supply chain and the calculation of grey water footprint using high-quality data may be explored in future research.

Compliance with Ethical Standards

Conflict of interest: The author(s) declare no actual, potential, or perceived conflict of interest for this article.

Ethics committee approval: Ethics committee approval is not required for this study.

Data availability: Data will be made available on request.

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Disclosure: -

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