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Evaluation of teff production in Ethiopia using water footprint analysis for food security

Etiyopya'da gıda güvencesi için teff üretiminin su ayak izi analizi ile değerlendirilmesi

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ABSTRACT

Achieving Sustainable Development goal (SDG)2; Zero Hunger by 2030 in Africa requires reconsidering the challenges of food security in relation to several factors including agricultural practices and water availability. Teff crop plays a significant role in Ethiopia but the yield is low due to rain-fed production practices. The water footprint (WF) concept provides a useful perspective on the dependency of crops on precipitation, revealing the need for irrigation. So, WF analysis of teff production can help farmers to increase the yield and maintain water efficiency. In this study, the green and blue water footprints of teff production in Ethiopia were estimated for 2019/2020 season using the CROPWAT 8.0 and CLIMWAT 2.0 models. The results show that WF_{green} is dominant with a value of 1170 m^3 ton^{-1} in Tigray region to 1481 m^3 ton^{-1} in SNNPR region. On the other hand, the WF_{blue} varied significantly from 264 m^3 ton^{-1} in Amhara to 1022 m^3 ton^{-1} in Tigray, respectively, indicating the need for irrigation since water requirement is much higher than the effective precipitation. The economic water productivity of teff was found to be 0.68 USD m^{-3}, which is higher than other crops such as maize. Given the potential impact of climate change and droughts, this study suggests increasing water allocation to teff production and implementing appropriate irrigation practices at a national level. Integrating water footprint analysis into river basin-level water allocation plans would be beneficial for sustainable water resource management and food security.

Key Words: Agriculture, Ethiopia, teff production, water footprint

ÖZ

Afrika'da 2030 yılına kadar Sürdürülebilir Kalkınma Hedefleri (SDG) arasında yer alan SDG 2: Sıfır Açlık hedefine yaklaşmak için, tarımsal uygulamalar ve su mevcudiyeti gibi çeşitli faktörlerle ilgili olarak gıda güvencesi sorunlarının yeniden gözden geçirilmesi gerekmektedir. Teff ürünü Etiyopya'da önemli bir yere sahiptir, ancak yağışa dayalı yetiştiricilik uygulamaları nedeniyle verim düşüktür. Su ayak izi (WF) kavramı, ürünlerin yağışa bağımlılığı hakkında yararlı bir bakış açısı sağlayarak sulama ihtiyacını ortaya koyar. Bu nedenle, teff üretiminin WF analizi, çiftçilerin verimi artırmasına ve su verimliliğini korumasına yardımcı olabilir. Bu çalışmada, Etiyopya'daki teff üretiminin yeşil ve mavi su ayak izleri, CROPWAT 8.0 ve CLIMWAT 2.0 modelleri kullanılarak 2019/2020 sezonu için tahmin edilmiştir. Sonuçlar, yeşil su ayak izi (WF_{green})'nin Tigray bölgesinde 1170 m^3 ton^{-1}, SNNPR bölgesinde ise 1481 m^3 ton^{-1} değeriyle baskın olduğunu göstermektedir. Öte yandan, mavi su ayak izi (WF_{blue}), Amhara'da 264 m^3 ton^{-1} ile Tigray'da 1022 m^3 ton^{-1} arasında önemli ölçüde değişmektedir. Bu sonuç, bitki su ihtiyacının etkili yağıştan çok daha yüksek olması nedeniyle sulama ihtiyacını göstermektedir. Teff'in ekonomik su verimliliği, mısır gibi diğer ürünlerden daha yüksek olarak 0,68 USD m^{-3} olarak bulunmuştur. İklim değişikliğinin ve kuraklığın potansiyel etkisi göz önüne alındığında, bu çalışma teff üretimine su tahsisini artırmayı ve ulusal düzeyde uygun sulama uygulamalarının gerçekleştirilmesini önermektedir. Su ayak izi analizini nehir havzası düzeyindeki su tahsis planlarına entegre etmek, sürdürülebilir su kaynakları yönetimi ve gıda güvencesi için faydalı olacaktır.

Anahtar Kelimeler: Tarım, Etiyopya, teff üretimi, su ayak izi

Introduction

According to FAO, almost 70% of the total number of people facing severe food insecurity are found in eight countries, five of which are in Africa including Ethiopia (FSIN, 2020). Africa has a large amount of fertile land and relies heavily on agriculture, but it only produces 10% of the world's agricultural output. This is due to issues such as low productivity, lack of investment, and policies that prioritize urban areas. These challenges have led to famines and poverty in many parts of Africa (AU, 2023). Additionally, the continent suffers from water shortages despite having abundant water resources, mainly due to uneven distribution and poor management. By 2025, even more African countries will face water stress, and a significant portion of the population will experience water scarcity. Sub-Saharan countries also don’t have adequate access to safe water and sanitation (WWF, 2023).

Teff (*Eragrostis tef*) is among the crucial sources of food security for African people, and it serves as a staple food for 85% of Ethiopia's population (Tadele and Hibistu, 2022). As the economy grows rapidly and cities become more populated, there is a greater need for teff in the food system, particularly in Ethiopia. Meeting the increasing demand for teff helps to improve the national policies on food and agriculture (Andreotti, et al., 2022). Apart from its importance for Africa, teff has also gained attention worldwide due to its high protein and amino acid levels, lack of gluten, and low glycemic index, making it a suitable choice for individuals with type 2 diabetes (Rosenberg et al., 2005).

Ethiopia accounts for over 90% of the world's teff production. Teff has the highest cultivated area share of any crop (24% in 2019/2020), followed by maize (18%), so teff is ranked second in terms of production volume in the country (CSA, 2020). Teff, besides being Ethiopia's second most significant revenue generator after coffee, brings in about $500 million annually for local farmers. Teff production is approximately 33% higher than coffee production (Minten et al., 2018; Mekonnen and Hoekstra, 2010). It is also grown in South Africa as a forage and cover crop, as well as in Northern Kenya as a cereal crop (FAO, 2023).

Most of Ethiopia's economy relies on agriculture, contributing to 70% of export earnings, 80% of employment, and 40% of the country's GDP (USAID, 2015). Teff production accounts for 7.6% of the real GDP (Moges, 2020*)*. Between 1997 and 2017, agriculture had the highest water consumption compared to other sectors, making it the largest water consumer (WB, 2017). Approximately 92% of all water withdrawals in the country (surface water and groundwater) are designed for agriculture, and water use is significantly higher than 70%, which is the global average (FAO, 2021). Although Ethiopia has a substantial amount of renewable water resources, less than 5% of it is used. Despite this, the country is still considered to be under "water stress" due to its fast-growing population. Ethiopia's renewable water supply was measured as 1,446 m^3 cap^{-1} $year^{-1}$, which is classified as "water-stress" according to the Falkenmark index (Daria, 2017).

Water availability impacts teff yield, which is highly variable among different parts of the continent. In South Africa, an annual teff production amount of 6,000 to 8,000 tons can be achieved by applying both irrigation and dryland methods, with a local production of at least 12,000 to 16,000 hectares (Agriorbit, 2023). However, in Ethiopia, the average teff yield is only 910 kg ha^{-1}, but by following effective agricultural practices, it is possible to consistently achieve yields of 2,000-

2,200 kg ha^{-1}. South African farms have already demonstrated the ability to reach these high yields, with reports of yields of 2,000 kg ha^{-1} (Biovision, 2022). On the other hand, in Ethiopia, the teff yield has reached 3300 kg ha^{-1}in experimental plots and farmers have achieved a maximum yield of 2500 kg ha^{-1}, but typically they produce 1000 kg ha^{-1}(Yihun, 2015).

According to the country's National Statistics Agency report (CSA, 2020), the highest amounts of teff are produced in Oromia and Amhara regions, accounting for around 85% of teff production volume and 84% of the planted area in the cropping season of 2019/2020. Southern Nations; Nationalities; and People's Region (SNNPR) and Tigray region are the third and fourth largest teff producing regions, respectively, despite their lower contribution to national teff output, estimated at 6.5% and 5.4% (CSA, 2020) (Table 1).

In Ethiopia, irrigation is underdeveloped and not widely practiced (CSA, 2020). In the 2019/2020 season, about 1.3 million farmers engaged in irrigation, covering a total area of approximately 211,047 hectares. The majority of the irrigated land was used for growing maize, sorghum, and teff, with maize occupying 53,670 hectares, sorghum 19,619 hectares, and teff 7,708 hectares. The majority of teff production during the 2019/2020 planting season relied on rainfall, as only around 0.25% of the entire teff plant area was irrigated (Table 1).

Table 1. Production data in priority teff producing regions

Region	Planted area (ha)	Irrigated area (ha)	Production		Yield (ton ha^{-1})
			(ton year^{-1})	(%)	
Oromia	1,487,971	2,226	2,809,098	49	1.88
Amhara	1,156,131	2,398	2,189,237	38	1.89
SNNPR	241,009	NA	380,420	7	1.58
Tigray	188,392	2,277	311,754	6	1.65
Total	3,073,503	7,708	5,690,509	100	-

Increasing teff yield is important for food security, hence its water requirement in a growing season should be fully met. Determination of teff's water footprint can help identify whether precipitation is adequate to meet its water requirement and whether/how much irrigation water is required. In this way, irrigation frequency and amount of irrigation water can be planned. Also, adequacy of the available water resources can be assessed.

The water footprint concept was introduced to measure how much water is used and polluted in production systems (Hoekstra and Hung, 2002). As a pressure indicator, it helps manage water resources, deal with water scarcity, adjust to changing consumption patterns, and improve water efficiency. There are two approaches to analyze water footprint; the first is the Water Footprint Network (WFN) approach and the second one is life cycle analysis (LCA). A significant difference between these methods is that LCA approach focuses on the product WFN approach focuses on water management (Lovarelli et al., 2016). The LCA approach is an international standard (ISO 14046:2014) (ISO, 2014), which adds impact assessment to the WF accounting.

Models can be used to estimate WF. For example, CROPWAT 8.0 is a program developed by the FAO, by which water requirements and irrigation schedule for crops based on climate, soil, and crop data can be calculated (Swennenhuis, 2009; Allen et al.,1998). It is widely used for determining the crop water footprints as recommended in the Water Footprint Assessment Manual. The program uses data from CLIMWAT 2.0 software to determine precipitation, crop growth inputs, and soil data to calculate water requirements. Once all variables are considered, the blue and green water footprints can be determined. CLIMWAT 2.0 is a climate database that works with the CROPWAT 8.0 software. It helps calculate water needs, irrigation supply, and scheduling for different crops and weather stations globally. The FAO's Water Development and Management Unit and the Climate Change and Bioenergy Unit worked on CLIMWAT 2.0, which offers data from over a thousand locations worldwide.

To accurately measure water usage in agriculture, it is required to take into account the amount of water evaporating from the soil, absorbed by plant roots, and evaporating from the plants themselves. The entire depth of precipitation required by the crop during times of growth is known as effective precipitation (P_{eff}) (Aldaya and Llamas, 2008). Effective precipitation is the WF_{green} that makes up a significant portion of water used in the different stages of agricultural production. The WF_{blue} of teff crop production was calculated as the blue component of crop water use, i.e. water from the groundwater or surface water such as rivers and lakes. Blue water is required when green water is not sufficient for crop growth (Hoekstra et al., 2011).

Previous studies estimated that Ethiopia's total annual water footprints were 77.8 billion $m^3 year^{-1}$ from 1996 to 2005 (Hirpa et al., 2022). The water footprints for crop production are primarily green (97%), with smaller proportions being blue (2%) and gray (1%). For industrial production, the water footprints are 5% blue and 95% gray, while for domestic water supply, they are 10% blue and 90% gray (Mekonnen and Hoekstra, 2011). A more recent study by WFN (2016) focused on the water footprints of major crops in Ethiopia, finding that 25% of the green water footprint is used for grazing and 75% for crop production. The study concluded that the annual green water footprint for agricultural production is 56.5 billion m^3, with a blue water footprint of 1.17 billion m^3. It also highlighted that the country is experiencing blue water scarcity in February and March, despite blue water only accounting for 2% of the overall water footprint.

The economic impact of the water footprint is related to inefficient water consumption. Water use efficiency can be considered at three scales: local, river basin, and global (Chapagain et al., 2006). The important question in agriculture is whether we can increase the amount of product we get for each unit of water. This can be measured as the amount of product per unit of water ($tons^{-3}$) or the economic value of the product (USD m^{-3}). The economic water productivity (EWP) is physically equal to the value obtained as a result of multiplying the water efficiency (unit of product per unit of water) by the price of the product (monetary value per unit of product).

Teff has not been extensively studied in terms of its water footprint at a national level. However, understanding and managing water consumption in agriculture is crucial for improving efficiency and sustainability. Tuyishimire et al. (2022) have found that the water footprint of food consumption has increased in Africa from 2000 to 2018. To this end, this study aims to assess the water footprint of teff production in Ethiopia, the leading producer in Africa, by measuring the green and blue water footprints using the CROPWAT 8.0 model (in $m^3 ha^{-1}$, $m^3 year^{-1}$ and $m^3 ton^{-1}$). The EWP was also calculated and compared to other crops. The findings can be used by decision makers to prioritize water use in the agricultural sector and potentially increase agricultural output to contribute to food security.

Materials and Methods

Study area

Oromia and Amhara regions, which account for 85% of total production and 84% of the cultivated area were considered. Additionally, SNNPR and Tigray regions, despite their smaller contributions to national teff production were included, as they are ranked third and fourth in production (CSA, 2020). These regions and rivers of Ethiopia are shown in Figure 1. Most of Ethiopia's river basins are interconnected and share regional territories.

Models used in the study

Data such as climate and teff crop characteristics were applied using the CROPWAT 8.0 model. The climate data of selected regions were taken from the CLIMWAT 2.0 software. The green and blue water footprints of teff crop were calculated following the framework presented by

Hoekstra and Chapagain (2002). WF_{blue} and WF_{green} of teff crops in each region was measured, considering the local climate and soil conditions. The amount of water used by the teff crops was calculated using the method and assumptions from Allen et al. (1998).

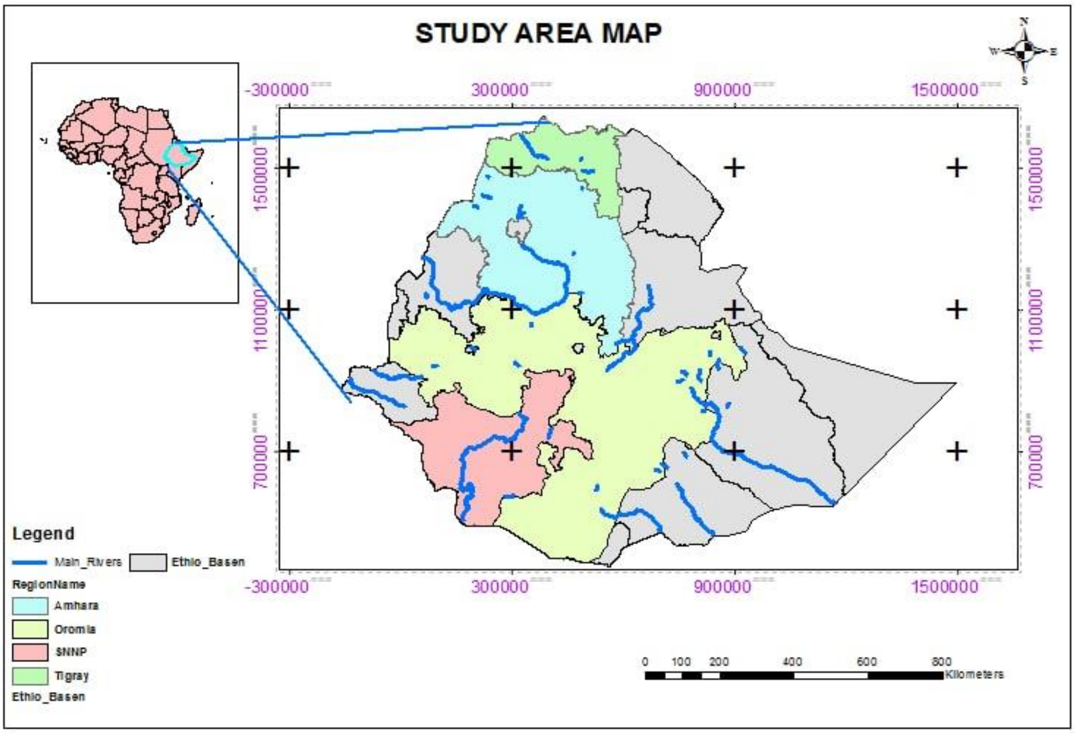


Figure 1. Ethiopian river basins and the largest teff producing regions

Evapotranspiration

Calculating evapotranspiration (ET_c) is essential to find the water footprints of crops. The ET_c of teff crop is available by the CROPWAT 8.0 software, which utilizes the FAO Penman-Monteith method for deciding reference crop evapotranspiration (ET_o). With this technique the ET_o of an area can be calculated based on the temperature, humidity, wind speed and sun data as given in Equation 1 (Allen et al., 1998).

$$ET_o = \frac{0.408\Delta(Rn-G)+\gamma\left(\frac{900}{Tmean+273}\right)u2(VPD)}{\Delta+\gamma(1+0.34u2)} \quad (1)$$

where;

ET_o	: daily reference evapotranspiration [mm day^{-1}] (For longer periods 900 becomes 37)
T_{mean}	: mean air temperature at 2 m height [°C]
VPD	: vapor pressure deficit [kPa]
u2	: wind speed at 2 m height [m s^{-1}]
Rn	: net radiation on the surface of the crop surface [MJ m^{-2} d^{-1}]
Δ	: slope vapor pressure curve [kPa °C^{-1}]
Γ	: psychometric constant [kPa °C^{-1}]
G	: soil heat flux density [MJ m^{-2} d^{-1}]

In this study, the "crop water requirement (CWR)" option was utilized, which means evapotranspiration was estimated under optimal conditions, i.e., crop evapotranspiration (ET_c) equals CWR (Hoekstra et al., 2011). The crop evapotranspiration (ET_c, mmday^{-1}) was calculated using Equation 2 (Mekonnen and Hoekstra, 2010; Allen et al., 1998).

$$ET_c = ET_o \times kc \quad (2)$$

where;

ET_c	: crop evapotranspiration (mmday^{-1})
ET_o	: reference evapotranspiration (mmday^{-1})
k_c	: crop coefficient

The kc values used for teff crop were obtained from literature (Yihun, 2015) and presented in detail in Table 2. These values represent the water consumption characteristics of teff crop during its different growth stages. Specifically, the crop coefficients for the initial, development, mid, and late stages were determined based on previous studies on teff growth under similar climatic and soil conditions, as outlined by Yihun (2015).

Green water footprint

Green water footprint (WF_{green}) equals the green effective precipitation (P_{eff}) if evapotranspiration (ET) is higher than the effective precipitation that occurs during plant growth. On the other hand, if evapotranspiration is lower than the effective precipitation, WF_{green} equals the green evapotranspiration as given in Equations 3 and 4 (Hoekstra and Chapagain 2002).

$$ET \geq P_{eff} \quad WF_{green} = P_{eff} \tag{3}$$

$$ET < P_{eff} \quad WF_{green} = ET \tag{4}$$

ET refers to actual evapotranspiration, which represents the water used by the crop (including both transpiration and soil evaporation) during the growing period. ETc (crop evapotranspiration) or ETo (reference evapotranspiration) were not used in these equations, as the focus is on the actual water used (ET) rather than potential water demand under ideal conditions (ETc or ETo).

Crop water use can come from either precipitation or irrigation. Green crop water use is calculated using Equation 5 (Hoekstra et al., 2011). The actual evapotranspiration was calculated from the day the teff crops were planted until harvest. In rain-fed vegetable crop production, blue crop water use (CWU_{blue}) is zero.

$$\mathrm{CWU\ green}\left(\frac{\mathrm{m3}}{\mathrm{ha}}\right) = 10 * \sum_{\mathrm{d=1}}^{\mathrm{lgp10}} \mathrm{ETgreen\ (mm)} \tag{5}$$

where;

ET_{green} : daily evapotranspiration green (mm day^{-1})

lgp : length of growing period (days)

D : factor of 10 to convert water depths in mm into water volume per hectare (m^3 ha^{-1})

The WF_{green} of teff crop production was calculated using Equation 6 as the total of rainwater evaporated from the area during the growth period. It is calculated as the green component of crop water use (CWU_{green}) divided by the yield (ton ha^{-1}) (Hoekstra et al., 2011).

$$\mathrm{WFgreen} = \frac{\mathrm{CWUgreen}}{\mathrm{Y}} (\mathrm{m3ton} - 1) \tag{6}$$

Blue water footprint

Decisively, if the evapotranspiration is higher than the effective precipitation, the blue water footprint (WF_{blue}) is potentially equal to the difference between the evapotranspiration and the effective precipitation. Otherwise, the blue water footprint is zero (Equations 7 and 8) (Hoekstra et al., 2011).

$$ET \geq Peff \quad WF_{\mathrm{blue\ theoretical}} = ET - Peff \tag{7}$$

$$ET < Peff \quad WF_{\mathrm{blue\ theoretical}} = 0 \tag{8}$$

CWU_{blue}, which is calculated using Equation 9, is equal to the difference of simulated total ET_c during the growing period and the use of green crop water. The summation is done from the first day the crops were grown until the end of harvest (Hoekstra et al., 2011).

$$\mathrm{CWU\ blue}\left(\frac{\mathrm{m3}}{\mathrm{ha}}\right) = 10 * \sum_{d=1}^{lgp10} ETblue\ (mm) \tag{9}$$

WF_{blue} (m^3 ton^{-1}) was calculated by dividing the CWU_{blue} (m^3 ha^{-1}) by the actual crop yield (Y) in ton/ha (Equation 10) (Hoekstra et al., 2011).

$$\mathrm{WF\ blue} = \frac{\mathrm{CWUblue}}{\mathrm{Y}} \left(\frac{\mathrm{m3}}{\mathrm{ton}}\right) \tag{10}$$

As previously mentioned, the aforementioned equations were used to calculate the green and blue water footprint of teff production for

Ethiopia's biggest teff producing regions, namely, Oromia, Amhara, Tigray, and SNNPR, in terms of m^3 ha^{-1} and m^3 ton^{-1}. The green and blue water footprint components were also computed in units of m^3 $year^{-1}$. The water footprint indicator, which reflects the annual volume of water consumed (m^3 $year^{-1}$), is determined by multiplying the water footprint value in m^3 ha^{-1} by the area (ha) where the teff crop was planted in 2019/2020 (Equations 11 and 12) (Hoekstra et al., 2011).

$$\mathrm{WFgreen}\left(\frac{\mathrm{m3}}{\mathrm{year}}\right) = \mathrm{WFgreen}\left(\frac{\mathrm{m3}}{\mathrm{ha}}\right) * \text{planted area}\left(\frac{\mathrm{ha}}{\mathrm{year}}\right) \quad (11)$$

$$\mathrm{WFblue}\left(\frac{\mathrm{m3}}{\mathrm{year}}\right) = \mathrm{WFblue}\left(\frac{\mathrm{m3}}{\mathrm{ha}}\right) * \text{planted area}\left(\frac{\mathrm{ha}}{\mathrm{year}}\right) \quad (12)$$

CROPWAT 8.0 input data

Water footprints were calculated using four types of data; meteorological, soil, crop parameter and yield for the period 2019-2020.

Meteorological data

The CLIMWAT 2.0 software was used to collect weather data from 93 weather stations in Ethiopia's Oromia, Amhara, SNNPR, and Tigray regions. This data includes monthly averages of climate data such as temperature, humidity, wind speed, sunshine, solar radiation, etc.

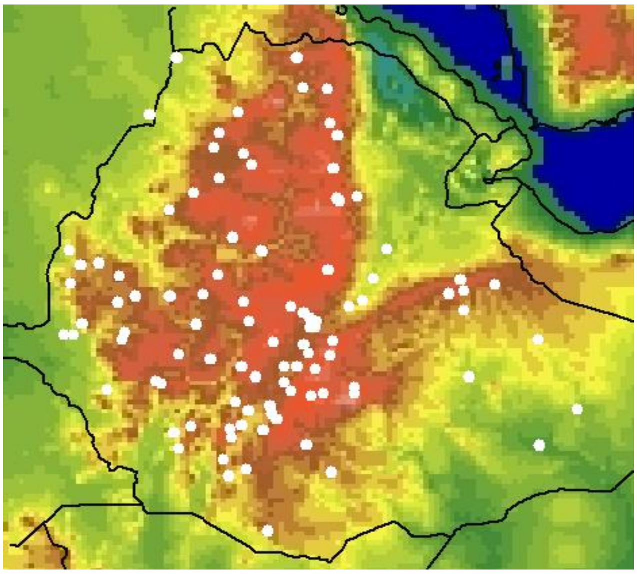


Figure 2. Weather station locations

The data from weather stations can be obtained in a format suitable for CROPWAT 8.0. Each station generates two files, one containing long-term monthly rainfall data and effective rainfall, and another containing average monthly values for climate factors, coordinates and altitude (FAO, 2022). The CROPWAT 8.0 software utilizes the Penman-Monteith formula to calculate evapotranspiration at each location. The USDA Soil Conservation Service formula is used to determine effective precipitation levels based on the total precipitation and monthly usage (Hoekstra et al., 2011).

Teff crop characteristics and soil data

The teff crop's crop coefficient, characteristics, planting and harvest dates were obtained from literature sources as they were not provided in the FAO 56 guideline. The data on teff crop parameters and the sources of literature used are listed in Table 2 (Desta and Almayehu, 2018). The plant depletion factor for teff is 0.50. The sowing and harvesting dates chosen for this study were July 15 and October 18. The overall yield response for teff production is 1.07, and the yield response factor (Ky) values vary throughout the growing season based on growth phases. The growth period of teff varies depending on the variety, and for this study, the DZ-01-976 variety with a growth period of 96 days was randomly selected.

Regarding soil information, if soil data is not available, the manual recommends using medium soil, which is a combination of heavy and light soil. In this study, medium soil was used. The production and yield of teff crops in 2019/2020 were obtained from the Ethiopian Central Statistics Agency annual report (CSA, 2020) The report indicated that the regions of Oromia, Amhara, Tigray, and SNNPR had the highest teff production in that year. Yield data for the 2019/2020 season were obtained from the Ethiopian Central Statistical Agency.

Table 2. Teff crop parameter data

Teff crop parameters	Growing periods				Reference
	Initial	Development	Mid	Late	
Crop coefficient (k_c)	0.6	0.8	1.2	0.8	(Yihun, 2015)
lgp (days)	36	12	24	24	(Desta, et al., 2018)
Rooting depth (m)	0.6	1.0			(Steduto, et al., 2012)
Depletion factor (%)	0.5	0.5	0.5		(Allen et al., 1998)
Yield response factor (k_y)	1.07				(Hilemicael, K. 2017)
Crop height (m)	1.0				(Steduto, et al., 2012)

In Ethiopia, teff crop mainly rely on rainfall, with only a small amount being irrigated. However, a computer program was used to calculate the optimal amount of water needed for teff crop, considering both rainfall and irrigation, if necessary. The program considers the ideal water requirements for the plants' growth and yield, even though the overall water usage for teff production is low. According to weather station data, the software CROPWAT 8.0 is used to determine that certain regions do not receive enough precipitation to meet the water needs of teff crop. Therefore, the software calculates both the precipitation and irrigation requirements for optimal crop growth. In other words, the water used by the teff crop in Ethiopia is mainly from rainfall, but the software calculates the additional irrigation water needed.

Water footprint of teff crop and the economic water productivity

It is calculated as the average producer's price of teff for the period 2019/2020 (USD ton^{-1}) divided by the total (green + blue) water footprint (m^3 ton^{-1}) (Equation 13) (Tewelde, 2019).

$$EWP = UP/WF_{total} \quad (13)$$

where;

WF_{total} : Total water footprint (m^3 ton^{-1})
UP : the product unit price (USD ton^{-1})

Results and Discussion

Effective rainfall and teff water requirement

CROPWAT outputs are given in Figure 3. The results show that Oromia, Amhara and SNNPR regions had teff water requirement (ET_c) of 287 – 298 mm in 2019/2020 period. On the contrary, teff water requirement was 359 mm in Tigray region, which is above the 260 - 317 mm value of Ethiopia (Araya et al., 2011). Despite having the highest water requirement, Tigray region received effective precipitation as low as 277 mm. On the other hand, the highest effective precipitation of 395 mm belonged to Amhara region. The country received 330 mm of effective precipitation on the average.

The average national teff green water requirement (ET_{green}) was recorded as 226 mm. The Amhara region had the highest ET_{green} of 245 mm, followed by Tigray region with the lowest, at 194 mm. On the other hand, the highest ET_{blue} belonged to Tigray, with a value of 169 mm. Other regions had similarly lower ET_{blue} values of 50 mm – 61 mm. The national average for ET_{blue} was found as 84 mm (Figure 3).

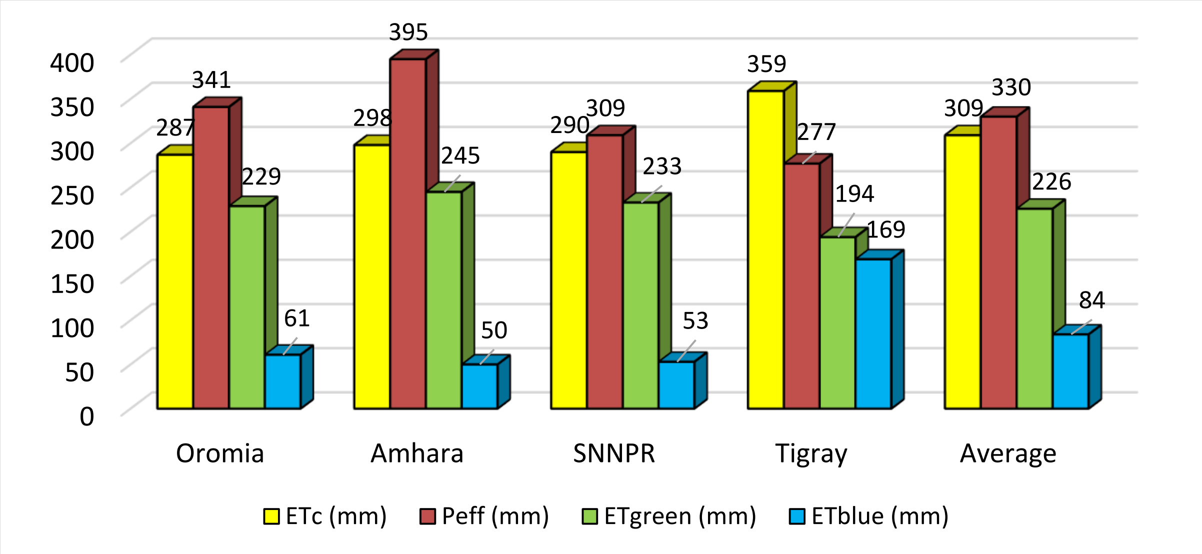
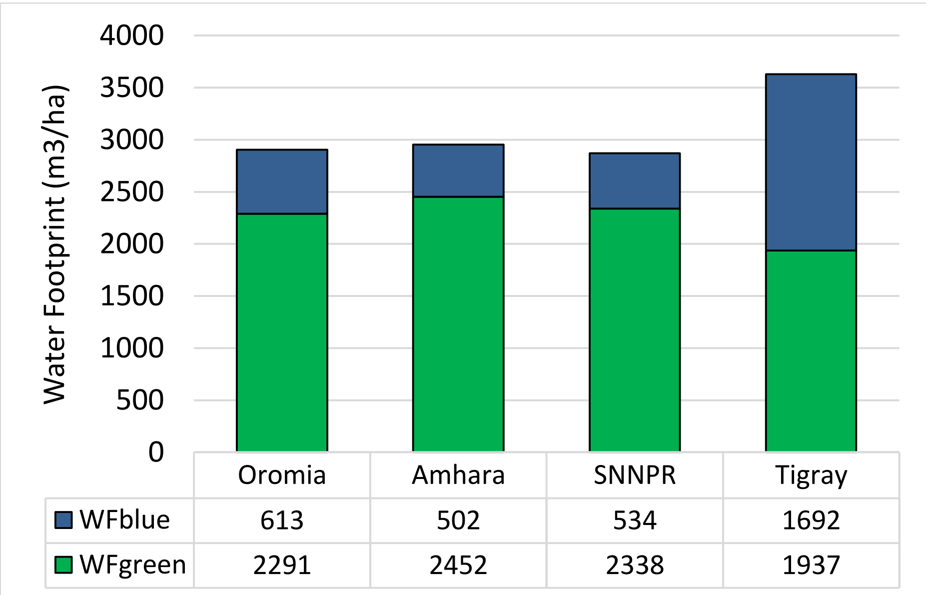


Figure 3. Teff water requirement, effective precipitation, green and blue water requirements

Water footprint of teff crop per area planted

When the WF values were calculated (Equation 9), it was found that teff in Amhara region had the highest WF_{green} with a value of 2452 m^3 ha^{-1}, followed by the SNNPR and Oromia regions (Figure 4). Teff in Tigray region had the lowest WF_{blue} with a value of 1692 m^3 ha^{-1}, which was about three times higher than those of other regions. A comparison of green versus blue WF showed that WF_{green} was four to five times higher than WF_{blue}, except for Tigray, where they were very close to each other. The average WF for growing teff in Ethiopia is 2254 m^3 ha^{-1} for green water and 835 m^3 ha^{-1} for blue water. The WF_{total} for teff production was 3089 m^3 ha^{-1}, which is representative of the national water footprint since the selected regions accounted for 99% of teff production.



	Oromia	Amhara	SNNPR	Tigray
WFblue	613	502	534	1692
WFgreen	2291	2452	2338	1937

Figure 4. Green and blue water footprints (m^3 ha^{-1}) of teff crop

Water footprint of teff crop per ton of product

The green, blue, and total WF of teff production were also calculated in m^3 ton^{-1} as a measure of water efficiency using Equation 10 (Figure 5). The nation's largest WF_{total} per ton of harvested teff was observed in SNNPR region with a value of 1481 m^3 ton^{-1}, close to the average value of 1280 m^3 ton^{-1}. This was followed by Amhara, Oromia and Tigray regions with similar values of 1295 - 1170 m^3 ton^{-1}. Regarding WF_{blue}, Amhara, SNNRP and Oromia regions had low values of 264 - 343 m^3 ton^{-1}, while Tigray region had significantly higher WF_{blue} of

1023 m^3 ton^{-1}. The average blue water footprint was 492 m^3ton^{-1} and the national average total water footprint was found to be 1772 m^3 ton^{-1}.

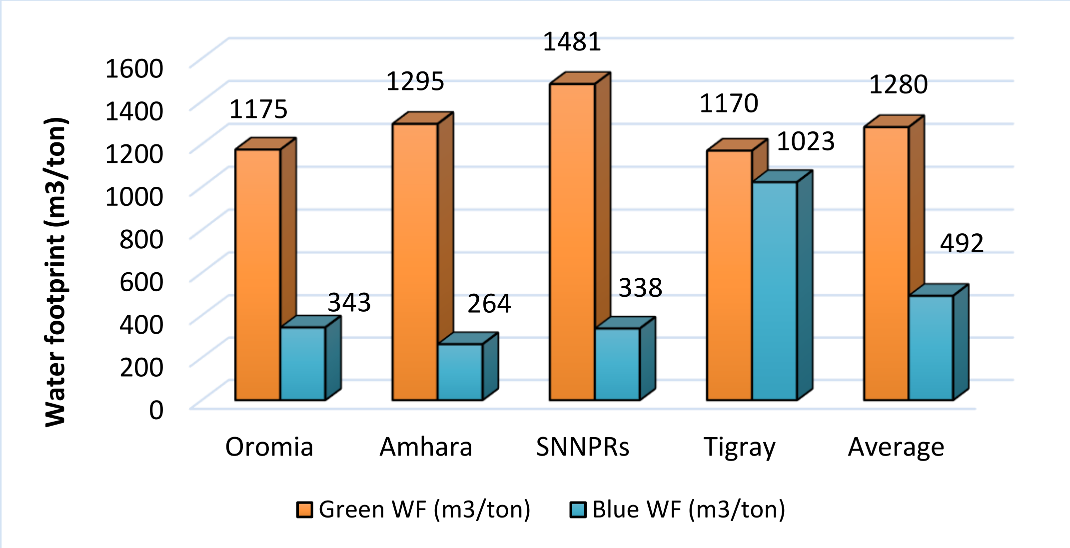


Figure 5. Green, blue and total water footprints per production quantity

A study by the WFN in 2016 found that maize mostly uses the green water, accounting for 22% of all green water footprints. Maize also has a combined water footprint of 4234 m^3 ton^{-1}, making it the third largest consumer of blue water (Figure 6). However, Mekonnen and Hoekstra (2010) had reported the global average WF of maize as 1222 m^3 ton^{-1}. Teff is the second most abundant crop in Ethiopia, and its green water footprint was 1280 m^3 ton^{-1}, reaching a total of 1772 m^3 ton^{-1} when including the blue water footprint. There may be differences in the calculation of water footprints between teff and maize due to climate, crop type, and calculation methods. Theoretical assessments of crop water use may overestimate the water footprint of crops (Fandika, 2019).

According to a recent study, the green and grey WF of teff was found as 4205 m^3 ton^{-1} and that of maize was found as 1940 m^3 ton^{-1} by Hirpa et al. (2022). The study also states that the green water footprint of the teff production was 3648 m^3 ton^{-1}, which is significantly higher than the 1280 m^3 ton^{-1} found in this study. The significant variations in crop water requirements and water footprints among the chosen crop varieties may be due to variations in growth stages and dates to maturity (Fandika, 2019). Hirpa et al. (2022) also state that spatial variation in climate, soil type, length of crop growing period (lgp) and fertilizer consumption affects and brings significant variation on the total amount of water footprint across locations. Another reason for this significant difference might be due to the fact that the study took the average teff lgp as 140 days but in this study the lgp of teff was taken as 96 days. A comparison of the results of this study with recent literature (Table 3) reveals that the national average blue water demand for the optimum gain in teff yield was highly variable. For example, WF_{blue} was found as 835 m^3 ha^{-1} in this study, however, teff production in the Debrezait area required more blue water; 1175 m^3 ha^{-1}, to meet the water that cannot be provided by available precipitation. Conversely, WF_{blue} was higher for Tigray region in this study, calculated as 1692 m^3 ha^{-1} (Figure 4).

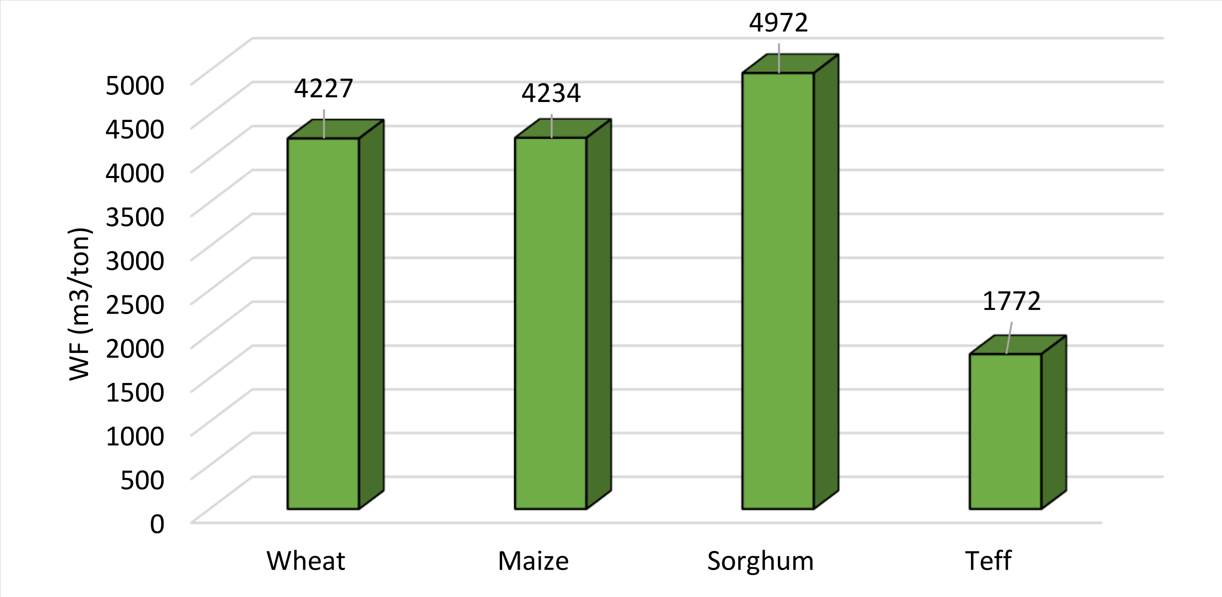


Figure 6. The water footprint of teff and other major crops in Ethiopia

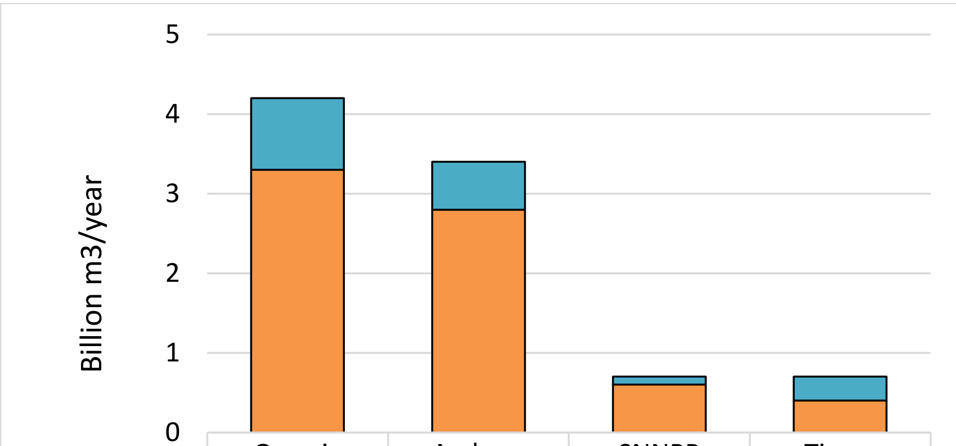
Table 3. Comparison of this study with literature

Product	This study				Literature (Hirpa et al., 2022)	
	WF_{green} (m^3 ha^{-1})	WF_{blue} (m^3 ha^{-1})	WF_{green} (m^3 ton^{-1})	WF_{blue} (m^3 ton^{-1})	WF_{green} (m^3 ton^{-1})	WF_{blue} (m^3 ha^{-1})
Teff	2254	835	1280	492	3648	1175

Water footprint of teff crop per year (m^3 $year^{-1}$)

The water footprints were converted to total annual values (Equation 11 and 12). Teff in Oromia and Amhara regions used the highest green water, with 3.3 billion m^3 $year^{-1}$ and 2.8 billion m^3 $year^{-1}$, respectively. Conversely, teff in Tigray and SNNPR regions used the least green water, with 0.4 billion m^3 $year^{-1}$ and 0.6 billion m^3 $year^{-1}$, respectively. Overall, a total of 7.06 billion m^3 $year^{-1}$ of national green water was used to grow teff during the growing season (Figure 7).

Regarding blue water footprints, with 0.9 billion m^3 $year^{-1}$, teff in Oromia had the highest value. The nation's overall blue water impact from teff production was 1.9 m^3 $year^{-1}$ (Figure 7). A total of 9 billion m^3 of water was used in teff production in 2019/2020. It was estimated that WF_{green} and WF_{blue} make up 78% and 22% of WF_{total}, respectively (Figure 8).



	Oromia	Amhara	SNNPR	Tigray
WF blue	0.9	0.6	0.1	0.3
WF green	3.3	2.8	0.6	0.4

Figure 7. Green and blue water footprints (Billion m^3 $year^{-1}$) of teff crop

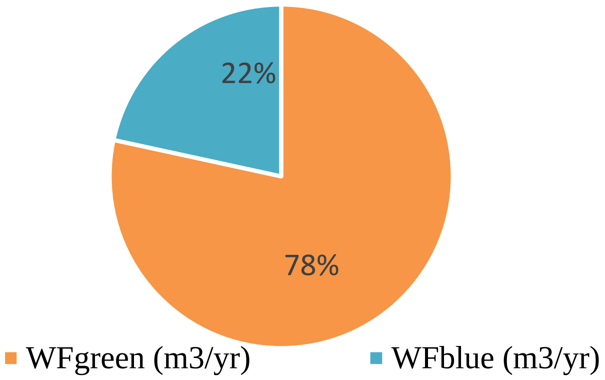
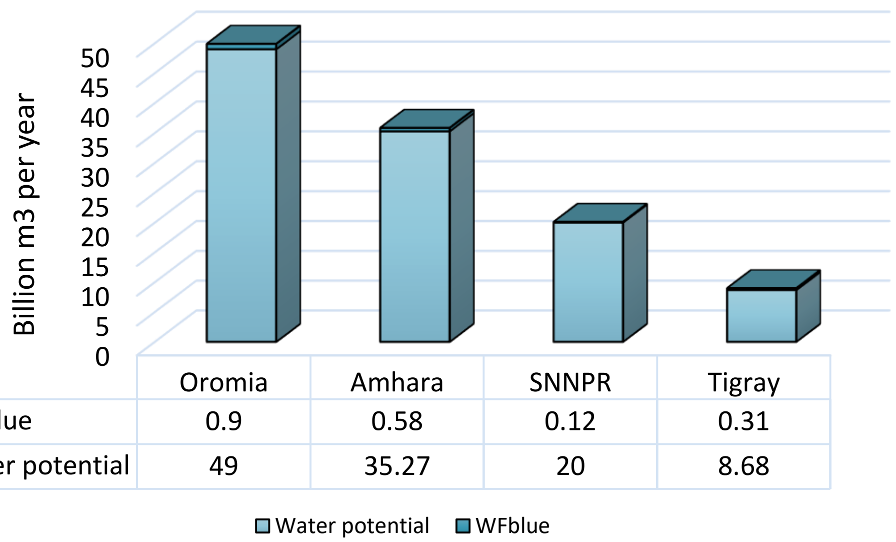


Figure 8. Share of green and blue water footprints

Figure 9 shows a comparison between the total WF of teff and the total water potential in four regions. In Oromia, the rivers have a water potential of 49 billion m^3 $year^{-1}$. If it is considered that teff cultivation requires both green and blue water, then 0.90 billion m^3 $year^{-1}$ of blue water is needed. This means that only 1.85% of the total water potential can be used for teff farming. However, this figure suggests that with additional irrigation techniques, teff can still be grown in the area, and the abundant water potential in the basin can help maximize teff production. The water footprint of teff was compared to the water potential of different regions. The Oromia region has a potential water capacity of 49 billion m^3 $year^{-1}$ and only 1.85% of it is needed for teff farming. On the other hand, teff in Amhara region requires water as low as 0.58 billion m^3 $year^{-1}$, which is about 1.63% of its water potential. Teff in Tigray region has the highest demand, needing 3.6% of its water potential.



	Oromia	Amhara	SNNPR	Tigray
WFblue	0.9	0.58	0.12	0.31
Water potential	49	35.27	20	8.68

Figure 9. Comparison of teff water footprint with water potential of regions

Economic water productivity of teff production

Teff is priced at 4200 Ethiopian Birr (77 USD) per 100 kg at the consumer level (Table 4), which displays the teff market chain for 2019/2020. The price of teff is substantially higher when it is processed into the finished product known as injera.

Table 4. Cost and price of the teff value chain (in Ethiopian units per quintal) (Jaleta, 2021)

Type of cost/price	Value (Birr per 100 kg)
Average cost for farmer	1800
Farmer's price	2600
Collector price	3200
Wholesaler price	3700
Retailer price	4200
Consumer's expected price	2411
Value-added teff to Injera	5600

The economic water productivity of teff in the October 2019-2020 season was found to be 0.68 USD m^{-3}. The EWP of maize, rice, and barley is lower than that of teff, with values of 0.003 USD m^{-3}, 0.26 USD m^{-3}, and 0.24 USD m^{-3}, respectively, according to a study conducted in Pakistan (Khan et al., 2021). The EWP can be high even if the price is low, but the water footprint is large, and vice versa. Using green water resources can be more financially beneficial and produce more income compared to using blue water resources, depending on the region. In Ethiopia, farmers should concentrate on improving water conservation techniques and effectively using green water in agricultural systems to enhance teff production. On the other hand, blue water might still be needed to help increase the yield. Unfortunately, due to various factors, about 24% of suitable teff land is expected to be lost between 2019 and 2050 (Yumba, MD, Kiambi, & Kebebew, 2014). To counteract this, it is important to improve agricultural practices and increase land productivity. This would not only lead to a decrease in water consumption but also make teff production more sustainable. To achieve this, measures such as seed selection, mulching, tillage, fertilizer application, and soil improvement should be implemented. In Ethiopia, teff is often planted late because farmers replace it after losing their first crop. However, in some areas, there is not enough rainfall for teff, so irrigation is needed. According to Yihun (2015), the current planting date for teff does not provide enough water, especially in the Tigray region with low rainfall. Planting during the rainy season does not give enough water due to unpredictable rainfall and droughts. Therefore, it is important to carefully plan the planting date or use irrigation to ensure optimal crop production. It was observed that irrigation has greatly increased teff grain yield.

Conclusion

Teff is an essential crop for Ethiopia's food security. Despite having enough water resources for irrigation, teff production in Ethiopia currently depends on rainfall, which is unpredictable due to droughts. Water footprint concept was used to figure out the adequacy of precipitation, irrigation water demand and the availability of water in corresponding regions. It was found that the amount of green water used in teff production in Ethiopia was much higher than the amount of blue water, with a range of 1170 m^3 ton^{-1} to 1481 m^3 ton^{-1} across different regions. The blue water usage varied greatly, ranging from 264 m^3 ton^{-1} to 1022 m^3 ton^{-1}, with the highest usage in the Tigray region, indicating the need for irrigation. Overall, the average total water footprint for teff production was 1777 m^3 ton^{-1}. The economic water productivity of teff, with a value of 0.68 USD m^{-3}, was found to be higher than those of other crops such as maize, rice, and barley.

In order for Ethiopia to improve its agriculture and maximize production, it must effectively plan and sustainably use its water resources. The study emphasizes the importance of green water, which is more influential in global food production than blue water. Despite having significant surface and groundwater resources, only a small portion is currently being utilized for irrigation. It is essential to utilize these water resources to enhance the efficiency of teff as well as other crops. Ultimately, the study suggests that increasing teff production, a staple crop for many Ethiopians, can help improve food security and move towards SGD 2 in the region.

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Declarations

Author Contributions

Meka Taher Yimam has conducted the study, collected data, used models, evaluated the results and wrote the manuscript. Gökşen Çapar has planned and supervised the study, evaluated the results and wrote the manuscript.

Conflict of Interest

The authors declare that there is no conflict of interest between them.

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