



# Water Footprint as an Emerging Environmental Tool for Assessing Sustainable Water Use of the Bioethanol Distillery at Metahara Sugarcane Farm, Oromiya Region, Ethiopia

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**Abstract** In Ethiopia, sugarcane estate farms and bioethanol distilleries are being expanded at an alarming rate to provide alternative sustainable energy as renewable, affordable, and low carbon footprint bioenergy for the transportation sector. The promotion of bioethanol production is definitely poised to cause high competition for water resources. Thus, the aim of this study was to investigate the water footprint (WF) of sugarcane molasses-based bioethanol production of the Metahara sugarcane farm. Ten years of meteorological data (2007–2016) were collected from the Metahara weather stations and processed through the CROPWAT 8 model using the Penman-Monteith method. Sugarcane coefficient ( $K_c$ ) was taken from FAO data; and sugarcane growing seasons, fertilizer application rates, sugarcane yield, and factory data were obtained from the Metahara factories. Reference evapotranspiration varied from 4.73 to 7.98 mm/day whereas effective rainfall ( $R_{eff}$ ) values ranged from 256.4 to 743.6 mm/growing season of sugarcane (16 months). The estimated sugarcane water requirement (SWR) ranged from 2544.1 to 4833.3 mm/growing season. The ANOVA test ( $p > 0.05$ ) for  $R_{eff}$  showed statistically insignificant differences in means but the test for SWR ( $p < 0.05$ ) revealed a statistically significant differences in means. The average sugarcane WF was 217.69 m<sup>3</sup>/t whereas the bioethanol WF was 3106.7 L/L. Hence, the WF of bioethanol production in the Metahara distillery is higher than the global average, indicating pressure on local water resources. Therefore, the results of this study may help policy makers to develop appropriate water resource management for the extensively growing sugar and bioethanol industries in Ethiopia.

**Keywords** Bioethanol · Environment · Evapotranspiration · Crop water requirements · Sustainability · Water footprint

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## Introduction

Competition for global freshwater consumption is increasing rapidly, largely due to the growing world population and the expansion of industrialization and modern agriculture, which have resulted in unsustainable use of groundwater, pollution of water bodies, depletion of water resources, and damage to ecosystems [1]. An increasing world population coupled with continued socioeconomic development put increasing pressure on the world's freshwater resources. Decreasing freshwater availability and quality are being observed across the globe [2]. An estimated 2.0–2.7 billion people will face water shortage problems by 2050 and the global water resources per capita will decrease by one third [3]. Overconsumption of freshwater is significantly contributing to water scarcity in many parts of the world. Water scarcity in agriculture and industries is estimated to result in a decline in GDP of about 6% in many nations by 2050 [4]. In addition to intensive water

abstraction across the globe, water pollution is a decisive factor aggravating water scarcity since polluted water is unsuitable for human use and diminishes water productivity.

The agricultural and industrial sectors are the main contributors to freshwater overutilization and pollution. Agriculture itself accounts for 86% of global freshwater consumption [5]. Agricultural freshwater demand is estimated to increase by 50% in developing countries and by 19% across the globe between 2000 and 2025 [6]. With the current agricultural water utilization efficiency and use rate (approximately 7100 km<sup>3</sup>/year), an additional 5700 km<sup>3</sup>/year of water will be needed to meet the world food demand by 2050 [7]. Globally, the gap between water resources and water demand is increasing due to anthropogenic activities and population increases, exacerbating the problem of water scarcity [8]. In the twenty-first century, declining freshwater availability and insufficient quantities and quality are major challenges for many societies and causes of conflicts over freshwater use, creating severe tensions between countries, regions, and even among sectors [9]. Hence, sustainable use and conservation of freshwater is critical to ensuring sustainability of socioeconomic development. Moreover, the aim of sustainable water use application is to implement innovative water management practices to ensure sufficient water quantity and quality for present and future generations.

Freshwater availability is a key factor for development of bioenergy crops such as sugarcane for bioethanol production. However, low priority is given to environmental impacts and sustainability of the biofuel industry in many African countries, including Ethiopia, since economic profits and job creation are the primary concerns of governments [10]. In reality, bioethanol distilleries are being developed at a fast pace because of the variability of oil prices on the world market and increasing consumption of bioethanol as an energy source and of raw plant materials by many industries [11]. Sugar factories annexed to bioethanol distilleries produce on average 95 kg of sugar, 12 L of bioethanol, 250 kg of bagasse, and 155 L of spent wash per 1000 kg of sugarcane [12]. The bioethanol distilling process requires large volumes of fresh water. Distillery waste accounts for 88 to 95% of the total volume of the raw materials in the bioethanol production process and bioethanol constitutes only the remaining 5 to 12% [13]. With respect to wastewater management, globally, about 80% of all wastewater is discharged without proper treatment [14]. For every liter of bioethanol produced, about 12 to 15 L of the distillery spent wash are generated [15]. At many places, most of the volume of the spent wash is not treated and is discharged into the nearby environment. This shows that bioethanol distilleries contribute significantly to water consumption and pollution along the supply chain of bioethanol production. Thus, proper water utilization and management tools such as water footprint (WF) are vital for sustainable water use.

The WF concept was introduced by Hoekstra (2002) as a tool for estimating freshwater consumption along the supply chain in the production of various products and to provide a useful indicator of water resources management [16]. WF is becoming a powerful environmental tool used by producers and consumers to assess water use along the production chain and to identify hotspots with the goal of ensuring continued availability of freshwater [7]. Thus, the ultimate goal of WF is to investigate the sustainability of freshwater use and to develop proper water management practices in different water-consuming sectors. Based on the application areas of interest, different units can be used to describe the water footprint concept for different sectors. Most commonly, WF is expressed as the water volume used per unit of product (usually mass, volume, energy, and piece) or the water volume per unit of time (year) in a delineated area (e.g., nation, municipality, province, or catchment) [16]. The WF of a product (m<sup>3</sup>/t) refers not only to the total volume of water used or polluted in order to produce a product but also to direct and indirect water uses in the production process. WF comprises green, blue, and gray water use expressed as an integrated freshwater resource allocation indicator; it permits more efficient water management than traditional limited water intake measurements [17]. Generally, WF is a more comprehensive and multidimensional indicator of freshwater consumption and pollution of a product within given geographical and temporal boundaries than the traditional measures of water withdrawal [18].

WF can be used as an indicator of water use to monitor and predict freshwater depletion and degradation in the production of water-intensive sugarcane crops and bioethanol. Globally, the rapid increase in the use of biofuels in the transportation sector has increased biofuel production, and the predicted global annual WF of biofuels in 2030 will be 10 times that in 2005 [19]. The heavy use of green, blue, and gray water is a major concern in sugarcane cultivation and bioethanol production [20]. Expansion of sugarcane cultivation is a global trend, important to the economic development agendas of many countries for future bioethanol feedstocks [21]. The global average WF of sugarcane was reported to be 209 m<sup>3</sup>/t, but wide variations in the WF of sugar and bioethanol production are reported from different countries [22]. In a study in Thailand, a sugarcane WF of 226 m<sup>3</sup>/t was reported, which consists of green (146 m<sup>3</sup>/t), blue (31 m<sup>3</sup>/t), and gray water (49 m<sup>3</sup>/t) [23]. Variations in WF are basically due to crop type, agricultural practices, climate conditions, and industrial water utilization efficiency [16].

Ethiopia is endowed with large areas of lowlands with climate and soil types suitable for sugarcane production. The Ethiopian government has given special attention to the development of sugarcane farms and sugar and bioethanol production. The government has expanded sugarcane plantations and bioethanol production with the vision to become the

leader of sugar and bioethanol production in Africa. Moreover, the tendency towards the utilization of bioethanol for transportation has recently increased in Ethiopia to meet the shortage of petroleum fuel and mitigate climate change and global warming. The promotion of bioethanol production will sharply increase water use in Ethiopia, where agriculture is the backbone of the economy and water management is poor.

Recently, Ethiopia has experienced drought mainly in the semi-arid area, resulting in declining agricultural yields. The focus of this study was to find favorable production conditions with respect to water consumption along the production chain and possibly hotspots and environmental burden on the local water system of the Metahara sugar factory and estate farm. Most sugarcane plantations and bioethanol industries in Ethiopia, including the Metahara bioethanol distillery, are located in the semi-arid climate zone, where sugarcane growing depends largely on surface water irrigation. Moreover, water is a precious resource and in very high demand in semi-arid areas, including the Awash valley, due to the fast expansion of large sugarcane estate farms and sugar industries. However, the amount of rain and irrigation water used by the Metahara farm for sugarcane production, sugarcane water requirement, and factory water demand has not been studied in an integrated way using the concept of WF. Furthermore, using WF clearly indicates an environmental pollution problem from the sugar industry and the leaching of excessive chemical fertilizer in the area. Hence, proper water management practices may generate environmental and economic benefits aimed towards ensuring sustainable sugarcane water use. Only a few studies [22, 24–28] exist on the WF of bioethanol production because of the complexity of data collection and the limitation of study methods. Furthermore, few WF studies have been conducted at local and regional levels in many countries, including Ethiopia. Global sugarcane and bioethanol WF studies are considered as a basis and trigger for more detailed local WF assessments [24]. However, investigations of the WF of bioethanol production under Ethiopian climate conditions, agricultural practices, and water management aspects are lacking. Therefore, this study aimed to quantify the WF associated with bioethanol production in the Metahara distillery based on sugarcane cultivation, molasses processing, and bioethanol production.

## Materials and Methods

### Description of Study Area

The Metahara sugar estate is the second largest irrigation scheme in the Awash Basin, shown in Fig. 1. It was established in an agreement between the Dutch company Handelsvereniging Amsterdam and the Ethiopian

government in 1965 to meet an increasing domestic sugar demand. Metahara is located in the East Shoa Zone, about 200 km east of Addis Ababa, in Oromiya Regional State, at the geographical coordinates of 8° 54' 0" north and 39° 55' 0" east. The area has a semi-arid climate, with mean maximum and minimum temperatures of 32.76 and 17.5 °C, respectively. The factory is at an altitude of 940 m above sea level and has an average annual rainfall of about 600 mm. There is no fixed rainfall trend in this semi-arid climate, but most of the rainy period is from June to September and the rest of months are dry. Currently, the Metahara sugar factory has about 10,230 ha of land covered with sugarcane with an average sugar production of 825,000 t/year and a bioethanol production capacity of 12,500 m<sup>3</sup>/year [29].

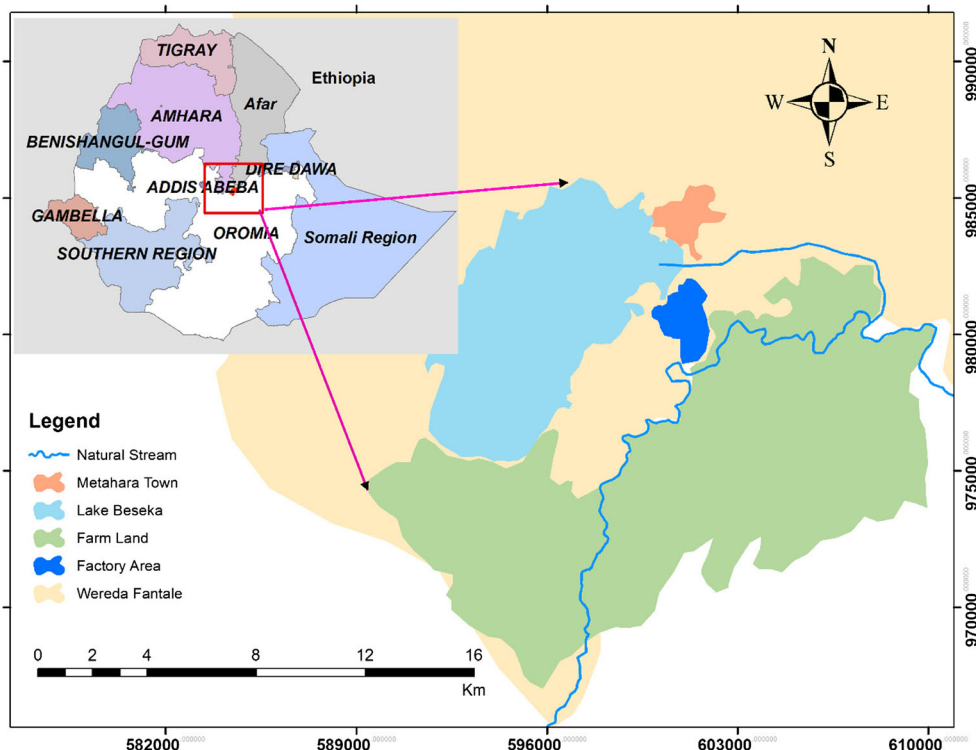
### Availability of Data and Materials

Meteorological data for the Metahara sugarcane estate farm, such as rainfall (mm), sunshine (h), relative humidity (%), maximum and minimum temperature (°C), and wind speed (m/s), were collected and processed through the CROPWAT 8 model. The meteorological data were arranged based on monthly average data and applied in the CROPWAT 8 model to estimate reference evapotranspiration ( $ET_0$ ). Sugarcane growing season (calendar), nitrogen fertilizer application rates (kg/ha), and sugarcane yield (t/ha) were obtained from the Wonji Research and Development Centre. Sugarcane coefficient ( $K_c$ ) values were taken from the Food and Agriculture Organization of the United Nations (FAO) data, which were used for initial, mid-season, and late season sugarcane growing stages. Furthermore, factory data were collected from the Metahara sugar factory and bioethanol distillery to estimate molasses and bioethanol WF. These factory data had two sections. The first comprised the data from the sugar factory, which included the amount of filter cake, molasses, bagasse, and sugar produced from 1 t of sugarcane processed in the factory. The second set of data was collected from the bioethanol distillery; these data included the amount of spent wash generated, process water consumed, and bioethanol produced from the molasses obtained from 1 t of sugarcane. Finally, additional process water consumed in the bioethanol distillery for fermentation, dilution, and distillation processes was considered. In all cases, 10 years (2007–2016) of data were collected and applied except for the bioethanol distillery, which was established in 2011; 5 years of data (2012–2016) were used for the distillery.

### Determination of Reference Evapotranspiration

Determination of evapotranspiration ( $ET_0$ ) refers to the estimation of evapotranspiration of an ideal (hypothetical) crop. A hypothetical reference surface assumes an extensive surface of green grass of uniform height, an actively growing crop

**Fig. 1** Locations map of Metahara sugarcane farm and sugar industry



height of 0.12 m, and a fixed surface resistance of 70 s/m [30]. This ideal  $ET_o$  condition can be related to actual crop water requirements (CWRs) using  $K_c$ . Although several methods exist to determine  $ET_o$ , the Penman-Monteith method is recommended [31]. Consequently,  $ET_o$  (mm/day) was computed from the Metahara weather station’s data of maximum and minimum air temperature ( $^{\circ}C$ ), wind speed (m/s), relative humidity (%), and sunshine duration (h) using the CROPWAT 8 model program by the FAO Penman-Monteith method.

**Calculation of Effective Rainfall**

Effective rainfall ( $R_{eff}$ ) refers to the portion of rainfall that can be effectively used by plants. Ten years (2007–2016) of rainfall data were used in the CROPWAT 8 model to estimate  $R_{eff}$ . The fixed-percentage method of effective rainfall calculation was used in this study; this is the recommended method for observed rainfall less than or equal to 100 mm/month.  $R_{eff}$  of actual precipitation was calculated according to Eq. 1.

$$R_{eff} = \text{fixed\%} \times R \tag{1}$$

where  $R_{eff}$  is effective rainfall (mm/day) and  $R$  is rainfall (mm/day) collected from the meteorological station. This fixed-percentage method indicated that about 20% of rainfall can be lost in the form of surface runoff or infiltration into the ground without utilization for crop growth [32].

**Determination of Potential Evapotranspiration**

Determination of crop evapotranspiration is basically the same as determination of sugarcane water requirement (SWR). The amount of water required to compensate for evapotranspiration loss from the cropped field is defined as CWR. Sugarcane evapotranspiration ( $ET_c$ , mm/day) was calculated for the given set of data on  $ET_o$  and  $K_c$ . Sugarcane  $ET_c$  value depends on climate  $ET_o$ , crop module, sugarcane growing season, and effective rainfall. The CROPWAT 8 model was used to determine SWR ( $ET_c$ ) with the help of Eq. 2.

$$ET_c \left( \frac{\text{mm}}{\text{day}} \right) = K_c \times ET_o(\text{mm/day}) \tag{2}$$

where  $ET_c$  is sugarcane evapotranspiration,  $K_c$  is the sugarcane coefficient, and  $ET_o$  is reference crop evapotranspiration [7].

**Green Water Footprint Calculation**

Green evapotranspiration ( $ET_{green}$ ) is the amount of effective rain water (mm/time) required to evaporate from the soil surface where crops are grown, including the transpiration of water that actually passes from crops plus the water incorporated in the product. Rainfall data were used to calculate  $R_{eff}$  in the CROPWAT 8 model using the rain module. If the  $R_{eff}$  is larger than the CWR, the  $ET_{green}$  is equal to the value of the

$ET_c$ , because a crop uses as much water as possible but never more than what is required for optimal plant growth [6]. In this analysis, the  $R_{eff}$  was smaller than the  $ET_c$ , thus the  $ET_{green}$  is equal to  $R_{eff}$  as shown in Eq. 3.

$$ET_{green} = (R_{eff}) \left( \frac{mm}{day} \right) \tag{3}$$

where  $ET_{green}$  is green evapotranspiration and  $R_{eff}$  is effective rainfall. The green component in sugarcane water use (SWU,  $m^3/ha$ ) was calculated by accumulation of all daily green evapotranspiration ( $ET_{green}$ , mm/day) over the entire growing period according to Eq. 4.

$$SWU_{green} \left( \frac{m^3}{ha} \right) = 10 \times \sum_{d=1}^{lgp} ET_{green} \tag{4}$$

where SWU is sugarcane water use,  $lgp$  is the length of the growing period (days),  $ET_{green}$  represents green evapotranspiration, and 10 is a conversion factor ( $0.1 \text{ mm/day} = 1 \text{ m}^3/ha/day$ ). Sugarcane green water footprint ( $WF_{green}$ ,  $m^3/t$ ) was calculated by dividing the green component in sugarcane water use ( $SWU_{green}$ ,  $m^3/ha$ ) by the sugarcane yield ( $Y$ , t/ha) according to Eq. 5.

$$WF_{green} \left( \frac{m^3}{t} \right) = \frac{SWU_{green}}{Y} \tag{5}$$

where  $WF_{green}$  is green water footprint,  $SWU_{green}$  ( $m^3/ha$ ) is green water used by sugarcane, and  $Y$  (t/ha) is sugarcane yield [23].

### Blue Water Footprint Calculation

Blue evapotranspiration ( $ET_{blue}$ ) is the sum amount of irrigation water (mm/time) required to evaporate from the soil surfaces, the amount of water transpired by plants, and the water incorporated in plants. The  $ET_{blue}$ , also known as the irrigation requirement (IR) (surface water), was calculated by taking the difference between the  $ET_c$  and the  $R_{eff}$ . If the  $R_{eff}$  is larger than the  $ET_c$ , the  $ET_{blue}$  is zero and no irrigation is required [33]. But in the study, the CWR is not fully met by  $R_{eff}$ . Hence, the  $ET_{blue}$  was calculated as the difference between the two values, as shown in Eq. 6 [34].

$$ET_{blue} = (ET_c - R_{eff}) \left( \frac{mm}{day} \right) \tag{6}$$

where  $ET_{blue}$  (mm/day) is blue evapotranspiration,  $ET_c$  (mm/day) is sugarcane evapotranspiration (mm/day), and  $R_{eff}$  is effective precipitation. The blue evapotranspiration of sugarcane is obtained by summing up the blue component of evapotranspiration over the growing period, using Eq. 7 [33].

$$SWU_{blue} (m^3/ha) = 10 \times \sum_{d=1}^{lgp} ET_{blue} \tag{7}$$

where SWU is sugarcane blue water use,  $lgp$  is the length of the growing period in days, and  $ET_{blue}$  represents blue water evapotranspiration. The blue water footprint ( $WF_{blue}$ ) of the sugarcane was taken from the ratio of the volume of irrigation water consumed ( $m^3/ha$ ) to the sugarcane yield  $Y$  (t/ha) according to Eq. 8.

$$WF_{blue} \left( \frac{m^3}{t} \right) = \frac{SWU_{blue}}{Y} \tag{8}$$

where  $WF_{blue}$  ( $m^3/t$ ) is blue water footprint determined from blue evapotranspiration,  $SWU_{blue}$  is sugarcane water use ( $m^3/ha$ ), and  $Y$  is sugarcane yield (t/ha) [7].

### Gray Water Footprint Analysis

Gray water footprint ( $WF_{grey}$ ) is the volume of water needed to dilute the pollutants that are emitted into a free-flowing water body using an accepted water quality standard.  $WF_{grey}$  was estimated according to Hoekstra et al. [18] by considering the effect of nitrogen fertilizer using Eq. 9.

$$WF_{grey} \left( \frac{m^3}{t} \right) = \frac{(\alpha AR)}{Yield \left( \frac{ton}{ha} \right)} \left( \frac{1}{(C_{max} - C_{nat})} \right) \tag{9}$$

where  $\alpha$  is the leaching-runoff fraction, AR is the chemical application rate to the farm field per hectare (kg/ha),  $C_{max}$  is the maximum acceptable concentration ( $kg/m^3$ ), and  $C_{nat}$  is the natural concentration of the pollutant in water bodies ( $kg/m^3$ ) [35]. The WF of sugarcane ( $m^3/t$ ) was calculated by summing the green, blue, and gray water footprint components as shown in Eq. 10.

$$WF_{sugarcane} = WF_{green} + WF_{blue} + WF_{grey} \tag{10}$$

### Molasses Water Footprint Calculation

The stepwise accumulative approach was used; it is the generic way of calculating the WF of molasses based on sugarcane WFs that include process water of each step. Hence, the WF of molasses was calculated according to Eq. 11

$$WF_{prod}(\text{molasses}) = \left( WF_{proc}(\text{molasses}) + \sum_i^y \frac{WF_{sugarcane}(i)}{f_p[p, i]} \right) f_v(p, i) \tag{11}$$

where  $WF_{prod} [p]$  ( $m^3/t$ ) is the water footprint of the product molasses;  $p$  is the product;  $i$  refers input;  $WF_{proc} (p)$  ( $m^3/t$ ) is the water footprint of the process;  $f_p[p, i]$  is product fraction of molasses;  $f_v[p, i]$  is the value fraction of the product (molasses), and  $WF_{prod} (i)$  ( $m^3/t$ ) is the water footprint of the product (molasses) [32].

The production fraction ( $f_p [p, i]$ , mass/mass) is defined as the ratio of the product mass (molasses, kg) to the aggregated mass of the crop (sugarcane, kg). The product fraction of the output product molasses processed from the input sugarcane was determined using Eq. 12.

$$f_p(p, i) = \frac{w(p)}{w(i)} \quad (12)$$

where  $f_p [p, i]$  is a product fraction (molasses unitless),  $w(i)$  is the mass of input (sugarcane in kg), and  $w(p)$  is the mass of product (molasses in kg).

The WF of all the products with economic value is represented by their value fraction  $f_v [p, i]$ . The value fraction of an output product ( $p$ ) is defined as the ratio of the market value of the product to the aggregated market value of all the outputs ( $p = 1$  to  $z$ ) obtained from the inputs (sugarcane), as shown in Eq. 13.

$$f_v(\text{molasses}) = \frac{\text{Price}(p) \times w(p)}{\sum_{p=1}^z \text{Price}(P) \times w(p)} \quad (13)$$

where  $f_v [p, i]$  is the value fraction of molasses and price ( $p$ ) refers to the price of product  $p$  (monetary unit/mass) and the  $w(p)$  is the mass of the products. The denominator is summed over the  $z$  output products (molasses, filter cake, bagasse, and sugar) using Eq. 13 [25].

### Bioethanol Water Footprint Calculation

Similarly, bioethanol WF ( $\text{m}^3/\text{t}$ , L/L) was calculated from sugarcane molasses WF. The input material was molasses, the by-product was the spent wash, and the product was bioethanol. Finally, the process water in the bioethanol distillery was also taken into account in calculating WF, as shown in Eq. 14

$$\text{WF}_{\text{prod}}(p) = \left( \text{WF}_{\text{proc}}(p) + \sum_i \frac{\text{WF}_{\text{prod}}(i)}{f_p[p, i]} \right) f_v(p, i) \quad (14)$$

where  $\text{WF}_{\text{prod}} [p]$  ( $\text{m}^3/\text{t}$ ) is the water footprint of the product (bioethanol);  $\text{WF}_{\text{proc}} (p)$  ( $\text{m}^3/\text{t}$ ) is the water footprint of the process;  $f_p [p]$  is the product fraction of bioethanol, and  $f_v [p]$  is the value fraction of the product (bioethanol) [22].

### Data Analysis

Using Microsoft Excel, descriptive statistical analysis and the one-way analysis of variance (ANOVA) test were used for data analyses. The ANOVA test was done for  $\text{ET}_o$  mean values comparisons of monthly data of the same year and the annual means of different years but not the seasons. However, other ANOVA tests were done for  $R_{\text{eff}}$  and SWR mean values of the monthly and yearly data of different growing seasons of sugarcane for the years of 2007–2016. ANOVA

was used to determine statistically significant differences between the means of the 10 independent measures of  $\text{ET}_o$ ,  $R_{\text{eff}}$ , and SWRs. The statistical analysis was performed at a 95% confidence interval. Meteorological data were operated using CROPWAT 8 model software for estimating  $\text{ET}_o$ ,  $R_{\text{eff}}$ , and SWR using the modules of climate/ $\text{ET}_o$ , rainfall, and crop.

## Results and Discussion

### Meteorological Data

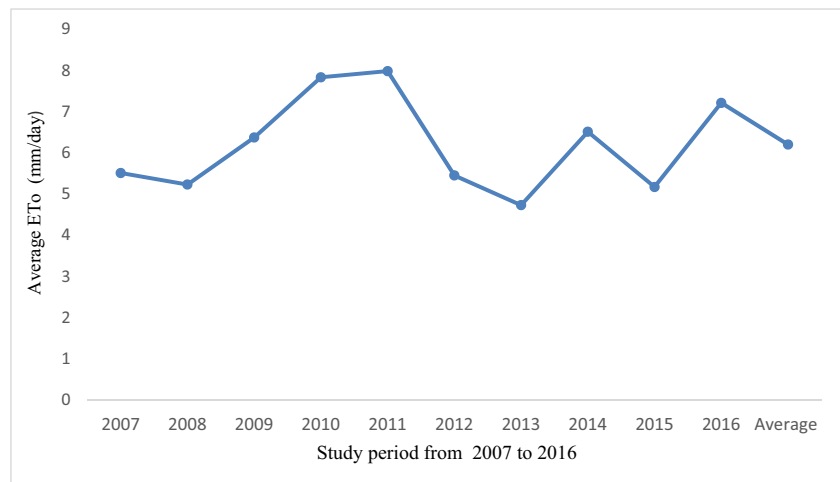
Weather conditions dictate the amount of energy available for evaporation and therefore play a crucial role in determining  $\text{ET}_o$ . Monthly minimum average temperatures ranged from 10.5 to 22.5 °C; maximum average temperatures ranged from 27.9 to 38.3 °C. There is a direct association between temperature and CWR. Evaporation increases with increased temperature because a higher amount of energy is available to convert liquid water to water vapor. The transpiration process is also increased because in warmer temperatures plants open up their stomata and release more water vapor. Transpiration rates increase by 20% when temperatures rise from 28 to 33 °C and by 30% when they rise from 28 to 35 °C [36].

Monthly relative humidity values ranged from 24 to 70%. Humid air decreases evapotranspiration and therefore also decreases SWR. This is the only input parameter in this study that suppressed the CWR of sugarcane and bioethanol WF. Wind speed was another factor that was considered as an input; it ranged from 0.9 to 8.9 m/s. The role of wind speed in evapotranspiration is to transport heat and accelerate evaporation by enhancing turbulent transfer of water vapor from moist crops to the dry atmosphere. Similarly, maximum and minimum monthly average sunshine ranged from 1.14 to 12.04 h over 10 years. Solar radiation is the largest energy source, capable of changing large quantities of liquid water into water vapor. Increasing sunshine hours is positively associated with evapotranspiration and enhanced sugarcane WF.

### Reference Evapotranspiration Calculation

The mean annual  $\text{ET}_o$  value ranged from 4.73 to 7.98 mm/day, as shown in Fig. 2. The average value of the  $\text{ET}_o$  over the study period was 6.2 mm/day. The  $\text{ET}_o$  values gradually increased from 5.51 mm/day in 2007 to a peak of 7.98 in 2011. This rise could be attributed to hot, dry weather conditions that directly influence evapotranspiration. The  $\text{ET}_o$  value gradually decreased after 2011. The fluctuation in  $\text{ET}_o$  value resulted from the variations in climate data, which affected crop evapotranspiration and WF. Normally,  $\text{ET}_o$  value depends on climatic conditions. Hence, the variation in  $\text{ET}_o$  clearly indicated the influence of the climate variability on SWR. However, this variation in  $\text{ET}_o$  was not statistically significant ( $p > 0.05$ ). A

**Fig. 2** Variations in  $ET_o$  over the 10 years of the study period



similar result was reported for sugarcane  $ET_o$ , which varied from 3.66 to 6.42 mm/day and used for SWR determination [37]. Generally, as the value of  $ET_o$  increases, CWR is expected to increase also.

### Effective Rainfall during Study Period

In order to calculate SWR, estimating the contribution of effective rainfall is very critical. The rainfall values ranged from 313.2 to 793.2 mm per year over the study period and the correspondence estimated effective rainfall to be in the range of 256.4–743.6 mm/season as shown in Fig. 3. This amount of effective rainfall is very minimal for SWR and clearly indicated the importance of the irrigation requirement under the study conditions. Furthermore, ANOVA performed for the mean variations in annual rainfall over this period showed the means statistically insignificant at  $P(0.75) > 0.05$ .

### Crop Evapotranspiration

Determination of crop evapotranspiration ( $ET_c$ ) was based on the calculation of  $ET_o$ , effective rainfall, and the crop module. In the crop module,  $K_c$  value, critical depletion, yield response, crop development stage, rooting depth, crop height, and plantation dates are the factors that were considered. The  $K_c$  factor serves as an aggregation of the physical and physiological differences between crops and the reference definition. In this study, the growing period started in December and extended for 16 months (480 days) until harvest. The growth stages for sugarcane were divided into four: 50, 70, 200, and 140 days, and were classified as planting (initial), crop development, mid-season, and late-season, respectively. As the crop develops, the ground cover, crop height, and leaf area changes reflect the differences in evapotranspiration during the various growth stages. The  $K_c$  values for sugarcane were 0.4, 1.25, and 0.75 at the initial stage, mid-season, and late-

season, respectively. Hence, SWR was determined from the interaction of the  $K_c$  and  $ET_o$  values.

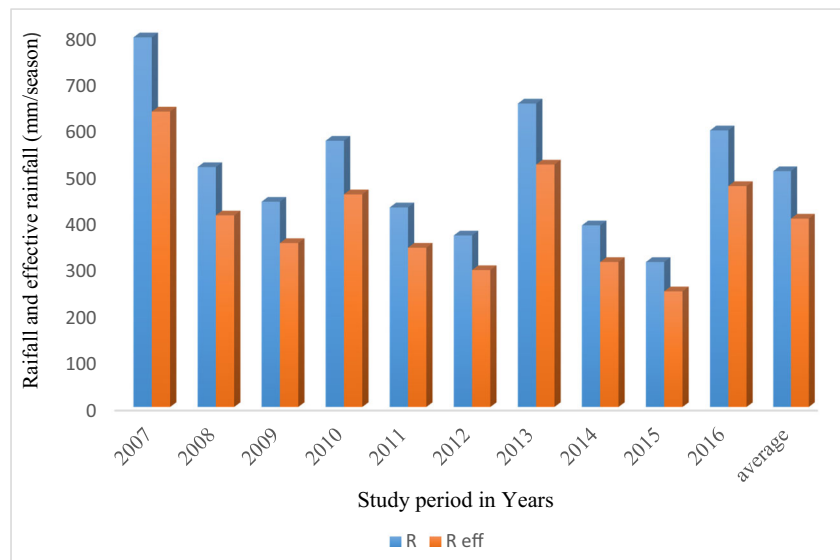
The observed SWR ranged from 2544.1 to 4833.3 mm/season (Fig. 4). This high variation in water requirement might be attributed to weather changes. The fluctuations in  $ET_c$  throughout the seasons are due not only to crop development, but also to climate conditions. Another reason for the large SWR was the long growing season of the sugarcane. Crop evapotranspiration increases with increasing air temperature and solar radiation, which are main drivers of  $ET_c$ . The high input of climate data into the CROPWAT 8 model resulted in the high CWR, but the contribution of  $R_{eff}$  to the total water requirement was insignificant. The average SWR during the growing period was 3495.2 mm, comprised of 448.6 mm  $R_{eff}$  per growing period and 3019.2 mm IR per growing period. Considerably lower SWR values (1715.2 mm) during growing periods have been reported [37]. In another study, a lower SWR range of 1233–2082 mm per growing season was reported for which the sugarcane yields varied from 31 to 119 t/ha [24]. The higher SWR of sugarcane at the Metahara farm indicates the need for improved water resources management practices.

### ANOVA of SWR

A one-way ANOVA was used to examine the relationship between the sugarcane growing period as the independent variable and SWR as the dependent variable (Table 1). ANOVA was used for testing the hypothesis that there were no differences between means of SWR over the study period. The alternative hypothesis stated at least one SWR mean was different from the others. The assumption was that populations are normally distributed, population variances are equal, and sampled observations are independent.

In this analysis, the null hypothesis was rejected at  $P < 0.05$  and the alternative hypothesis was accepted because there was a statistically significant difference among

**Fig. 3** Annual and effective rainfall trends of Metahara sugarcane farm.  $R$  = rainfall and  $R_{\text{eff}}$  = effective rainfall



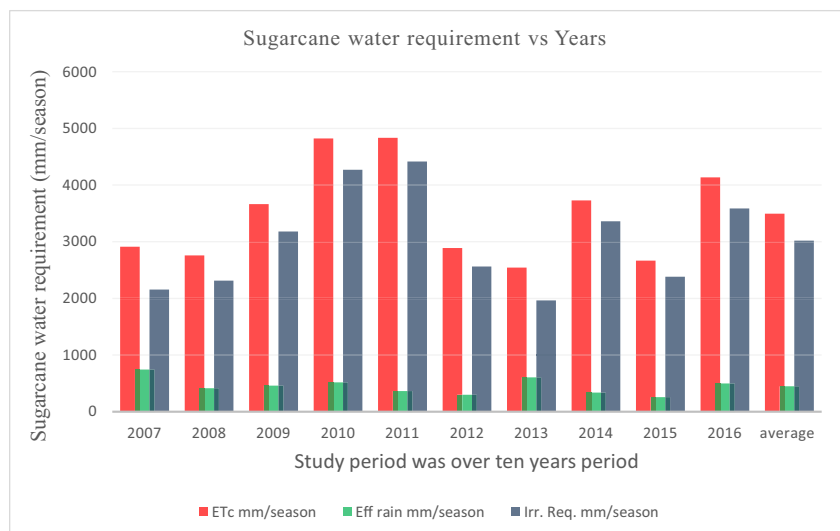
SWR means. But there is no sufficient evidence to determine which SWR mean was different from the others. It can be concluded that the independent variable influenced the response variable, but the analysis does not identify the specific growing season that was different from the other seasons.

### Sugarcane Water Footprint Analysis

The annual sugarcane yield over the 10 years ranged from 119.4 to 185.30 t/ha, with an average yield of 161.15 t/ha. However, Brazil, the largest sugarcane producer, which accounts for 34% of the world’s production, obtains an average yield of 75.2 t/ha, India harvests 63.4 t/ha, Thailand 75.7 t/ha, Pakistan 56.5 t/ha, the USA 75.7 t/ha. Cuba 39.9 t/ha, and Peru 133.7 t/ha [35]. Surprisingly, Ethiopian sugarcane yield

is very high, a fact that significantly suppresses the sugarcane WF directly and the WF of bioethanol indirectly. However, the extremely high yield might be attributed to the fertile soil and climatic conditions conducive for sugarcane growing in the tropical region. The  $ET_{\text{green}}$  ranged from 256.4 to 743.6 mm/season, with an average value of 448.6 mm during the growing period. Then, the  $SWU_{\text{green}}$  was 4486 m<sup>3</sup>/ha and the green component of sugarcane WF was 27.84 m<sup>3</sup>/ha. In the agricultural sector, blue water consumption depends on crop variety, crop tolerance to water deficits, irrigation efficiency, and the existence of green water in the area. Inadequate  $R_{\text{eff}}$  required that most of the water for SWR came from IR. IR ranged from 1962.3 to 4416.3 mm/season, with an average value of 3019.2 mm during the growing period. Thus, the  $SWU_{\text{blue}}$  was 30,192 m<sup>3</sup>/ha and the WF of the blue component was 187.35 m<sup>3</sup>/t.

**Fig. 4** Contribution of  $R_{\text{eff}}$  and IR to total SWR at Metahara sugarcane farm. ETC is sugarcane water requirement, Eff rain is effective rainfall, and Irr. Req. is the irrigation requirement



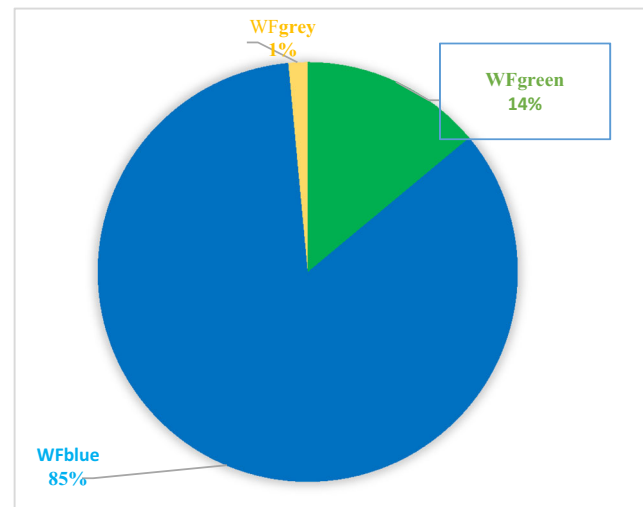


**Table 1** ANOVA test for SWR

Source of variation	SS	df	MS	F	P value	F crit
Between groups	143,620.5	9	15,957.83	45.16	0.00	1.99
Within groups	166,080.5	470	353.36			
Total	309,701	479				

$WF_{grey}$  is the volume of freshwater that dilutes the wastes, mostly fertilizers and pesticides, generated during sugarcane cultivation.  $WF_{grey}$  is therefore an indicator of freshwater pollution. For  $WF_{grey}$  calculation, the nitrogen leaching runoff fraction is assumed to be 10% [38]. The Ethiopian Ministry of Environment, Forest and Climate Change (EFCC) and WHO recommend the concentration of nitrogen ( $NO_3-N$ ) must not exceed 50 mg/L [39]. Thus, 0.05 kg/m<sup>3</sup> of nitrate was used as an acceptable concentration in fairly clean fresh surface water. But the zero value was considered for concentration of nitrate in natural water bodies [20]. The rate of urea fertilizer applied in the study area varied between the two soil fertility groups of the Metahara farm. Recently, the sugarcane farm has used urea fertilizer applied at a rate of 170 and 230 kg/ha for soil fertility groups F1 and F2, respectively. The F1 soil fertility unit area covers 63% of the Metahara sugarcane farm (10,230 ha) and the rest of the sugarcane farm accounted for 37% (F2). Then, the average fertilizer application rate was 207.8 kg/ha. The estimated gray component of the sugarcane WF was 2.58 m<sup>3</sup>/t. However, only nitrogen fertilizer pollution was considered to estimate the  $WF_{grey}$ . Practically, some other nutrients and pesticides may cause more water pollution than the nitrogen, but they were not considered due to lack of specific analytic methods in the literature. Finally, the WF components of sugarcane—the green, blue, and gray—were 27.84 (12.8%), 187.35 (86.1%), and 2.58 m<sup>3</sup>/t (1.1%), respectively. The contribution of each component is clearly indicated in Fig. 5. The total estimated total WF of Metahara sugarcane is 217.69 m<sup>3</sup>/t.

The proportion of the  $WF_{grey}$  has been reported to vary between 4 and 11% in sugarcane farms in different countries [32]. But the contribution of the  $WF_{grey}$  to the total WF of the Metahara sugarcane is only 1.1%, which is very insignificant. Ignoring the concept of WF, the water consumption of this study area is high, but the WF concept relates the water consumption with the amount of product it generates. The great limitation of the  $WF_{grey}$  calculation is the fact that it was based on the leaching rate of nitrogen fertilizer only. Generally, the Metahara sugarcane WF (217.69 m<sup>3</sup>/t) falls in the upper two thirds of the global range of values (120–410 m<sup>3</sup>/t) [22]. A WF study conducted in Thailand reported 226 m<sup>3</sup>/t sugarcane WF, consisting of green (146 m<sup>3</sup>/t), blue (31 m<sup>3</sup>/t), and gray WF (49 m<sup>3</sup>/t) [38]. Other relatively low values of sugarcane WF were recorded under different management practices in Brazil ( $WF_{green}$  145,  $WF_{blue}$  38, and  $WF_{grey}$  18 m<sup>3</sup>/t) [35] and from

**Fig. 5** Contribution of each component of sugarcane WF

the Paranaíba Basin in Brazil for rain cultivated (151 m<sup>3</sup>/t) and irrigation cultivated (142 m<sup>3</sup>/t) sugarcane WF [20]. These differences in WFs appear to be largely due to differences in climate, sugarcane yields, and rate of nitrogen fertilizer application.

### Molasses Water Footprint Analysis

Molasses is the residual syrup obtained by centrifugation from cane juice not forming crystalline sugar. In this study, the products and by-products of the sugar factory are bagasse, filter cake, sugar, and molasses whereas the input material was sugarcane, as shown in Table 2. Based on the distribution of these materials, the product fraction and value fraction of molasses were determined.

In the Metahara sugar factory, 1 t of sugarcane generated on average 34.0 kg of molasses, 297.7 kg of bagasse, 29.6 kg of filter cake, and 100 kg of sugar. The average annual sugarcane production at Metahara through the study period was 106,728.5 t and molasses production was 36,604.4 t. Hence, the molasses production fraction was 0.04. The economic value of bagasse was calculated based on the amount of electricity it generated, whereas the value of filter cake was determined from the economic value of fertilizer. The rate of fertilizer application was reduced from 230 to 170 kg/ha (by 60 kg) when the farm started to use filter cake as a fertilizer at the rate of 30 t/ha during the study period. The average price of 100 kg of fertilizer in Ethiopia was 1100 Birr during the study period and the price of filter cake was only 660 Birr/30 t (22 Birr/t). On the other hand, 1 t of sugarcane bagasse generated 0.2 kWh of electricity within the old boiler of Metahara. The price of electricity in Ethiopia was 0.69 Birr/kWh. On average, the price of 100 kg of white sugar was 690 Birr and the price of sugarcane molasses was 232 Birr/100 kg. Using

**Table 2** Sugar factory data with the product and value fractions of the molasses

Year	Sugarcane	Sugar	Bagasse	Filter cake	Molasses	Molasses $f_p$
2007	11,704,193	1,264,025	3,400,418	426,757	414,553	0.035419
2008	11,305,414	1,302,661	3,210,388	386,137	410,822	0.036339
2009	12,130,022	1,301,804	3,460,642	376,335	424,823	0.035022
2010	12,032,489	1,200,343	3,932,880	396,409.7	416,791	0.034639
2011	10,014,000	1,019,623	2,720,078	232,439	323,765	0.032331
2012	9,829,652	931,399	2,840,053	201,401	309,669	0.031504
2013	9,019,313	797,983	3,242,984	336,579.8	288,984	0.032041
2014	11,555,499	1,149,000	3,544,087	349,731	436,850	0.037805
2015	11,011,609	1,110,515	3,128,629	258,948.3	380,011.1	0.03451
2016	7,870,662	698,661	2,196,887	212,504.4	254,170	0.032293
Average	10,647,285	1,077,601	3,167,705	317,724.2	366,043.8	0.04000
Year		S/SC ratio	B/SC	F/SC	M/SC	fv(M)
2007		0.107998	0.29053	0.036462	0.035419	
2008		0.115225	0.283969	0.034155	0.036339	
2009		0.107321	0.285296	0.031025	0.035022	
2010		0.099758	0.326855	0.032945	0.034639	
2011		0.10182	0.271628	0.023211	0.032331	
2012		0.094754	0.288927	0.020489	0.031504	
2013		0.088475	0.35956	0.037318	0.032041	
2014		0.099433	0.306701	0.030265	0.037805	
2015		0.100849	0.284121	0.023516	0.03451	
2016		0.088768	0.279124	0.027	0.032293	
Average		0.10044	0.297671	0.029639	0.03419	0.103
kg/t of sugarcane		100.4	297.7	29.6	34	

All parameters in the table are given in unit of quintal

S sugar, SC sugarcane, F filter cake, B bagasse, M molasses

these data, the estimated value fraction of molasses was calculated to be 0.10 (in all cases US\$1 = 23.32 Ethiopian Birr).

The process water is the water used in the sugar factory to transform sugarcane into molasses by-product through the process of juice extraction, clarification, evaporation, and centrifugation. Usually, process water used for a sugarcane factory varies between 1 and 21 m<sup>3</sup>/t [25], a very small amount compared to the average water consumption for sugarcane growth [25, 32, 40]. Thus, water of 10.5 m<sup>3</sup>/t of sugarcane was considered for this study. Based on these data, the average estimated molasses WF of 553.6 m<sup>3</sup>/t was obtained, composed of 76.65 m<sup>3</sup>/t of green, 469.43 m<sup>3</sup>/t of blue, and 7.3 m<sup>3</sup>/t of gray components. This value was high compared to the average value in another study (407 m<sup>3</sup>/t) [38], which indicates high water consumption and pollution in the bioethanol production process occurred in the Metahara sugar factory.

### Bioethanol WF Determination

Molasses is used as feedstock for bioethanol production, which involves pre-treatment, fermentation, distillation, and

dehydration processes. In these processes, the amount of bioethanol and spent wash produced from 1 t of molasses with process water consumed are shown in Table 3. To allocate the WF of the sugarcane-based molasses over its bioethanol distillery products, molasses WF was used.

In the bioethanol production process, the main product was bioethanol and the by-product considered was spent wash. The economic value of all the by-products influence the WF of bioethanol. Spent wash is the wastewater generated by the distillery and often used as fertilizer, reducing other fertilizer consumption by 25%. The estimated total fertilizer cost of sugarcane cultivation in Ethiopia was 2200 Birr/ha; this price accredits 550 Birr/ha for spent wash [25]. The amount of spent wash per ton of sugarcane was 0.12 m<sup>3</sup>/t whereas the sugarcane yield per hectare of the study area was 161.15 t/ha. Finally, the cost of the fertilizer reduced (550 Birr/ha) related to the amount of spent wash consumed (18.5 m<sup>3</sup>/ha) was used to estimate cost of spent wash (29.73 Birr/m<sup>3</sup>). Moreover, the average amount of process water consumed in the bioethanol distillery was 4.15 m<sup>3</sup>/t. The estimated product fraction of bioethanol was 0.22. On average, 9.46 L of bioethanol was produced from molasses originating from 1 t of sugarcane.

**Table 3** Products and process water consumed in the bioethanol distillery

Time (year)	Molasses (t)	Bioethanol (L)	Process water (m <sup>3</sup> )	Spent wash (L)
2012	1	284.53	4.12	3244.46
2013	1	279.26	3.8	5528.69
2014	1	240.73	3.61	2874.02
2015	1	250.12	4.32	2831.51
2016	1	233.17	4.90	2399.44
Average	1	257.56	4.15	3375.62

The average local price of 1-L bioethanol was 11.95 Birr. Hence, the estimated value fraction of bioethanol was 0.997. For unit conversion of bioethanol WF (from m<sup>3</sup>/t into L/L), ethanol density (0.789 kg/L) was used. Finally, the average amount of bioethanol WF at the Metahara distillery was 3106.7 L/L; this figure comprises the green (433.43 L/L), blue (2627.38 L/L), and gray (45.89 L/L) WFs. The contribution of WF<sub>grey</sub> to total WF in bioethanol production was really insignificant, as indicated in Fig. 6.

In this study, the estimated bioethanol WF is higher than the global average (2855 L/L). This indicates that the production of bioethanol is exerting pressure on the local water resources. In another study, a lower value of bioethanol WF of 2415.7 L/L was reported [23]. Largely, the WF of cane-based bioethanol varied from Peru (1670 L/L), Brazil (2450 L/L), USA (2775 L/L), India (2995 L/L), and Cuba (6355 L/L), and the weighted global average was 2855 L/L [24].

## Conclusion

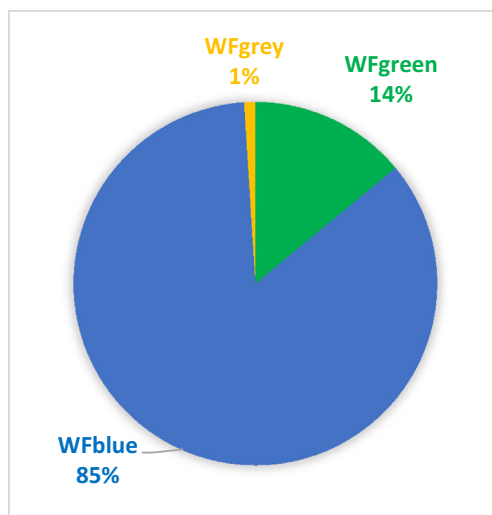
High SWR (3495.2 mm/growing season) at the Metahara sugarcane farm is attributed to climatic factors and water resource management in combination with prevailing agricultural practices. This high SWR may be reduced with better agricultural

and sugarcane processing practices. The average sugarcane WF at Metahara (217.69 m<sup>3</sup>/t) was higher than the global average. Exceptionally high sugarcane yield at Metahara (161.15 t/ha) suppressed the sugarcane WF of 217.69 m<sup>3</sup>/t to a certain extent. Nevertheless, the relatively high sugarcane WF is one of the areas in the production chain of bioethanol that needs to be addressed to ensuring the sustainability of local and regional water resources. The average bioethanol WF of 3106.7 L/L was obtained, indicating that bioethanol production significantly impacts water resources by alleviating local water stress in sugarcane cultivation. An additional 252.7 L of bioethanol WF is applied per liter of bioethanol in the Ethiopian context, particularly at Metahara, compared to the global average bioethanol WF. This showed that there is ample room for improvement, further indicating the need to reduce the WFs of sugarcane and bioethanol production. Therefore, sustainable sugarcane/bioethanol production and lesser dependence on fossil fuel for transportation require reductions in water use and pollution through more efficient production processes as well as judicious fertilizer and pesticide applications. Furthermore, the results of the study may also inform government officials or policy makers as they seek to improve water resources management of this sector.

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**Fig. 6** Contribution of each component of bioethanol WF

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