Journal of Environmental Science and Management Special Issue 1-2023: 66-78 ISSN 0119-1144

Water Footprint of Bioethanol Production in Negros Occidental, Philippines

ABSTRACT

This study investigates the water scarcity implications of bioethanol production in Negros Occidental, Philippines. The water footprint (WF) of three bioethanol production scenarios was assessed, revealing respective values of 3,574 L L^{-1}, 3,935 L L^{-1}, and 4,293 L L^{-1} for Case 2 (molasses bioethanol), Case 3 (50% sugarcane and 50% molasses bioethanol), and Case 1 (sugarcane bioethanol). Predominantly, 99% of the total WF comes from sugarcane plantation activities, with the blue WF (freshwater use) accounting for a mere 1.3%, owing to predominantly rainfed sugarcane farms. Region VI, encompassing Negros Occidental, faces severe blue water scarcity at 41%, with projections indicating exacerbation unless water footprint mitigation strategies are implemented. Notably, the contribution of the bioethanol industry to the total WF of the region is only about 0.1%. Sensitivity analysis for varying sugarcane yield done revealed that increasing yield from 65 t ha^{-1} to 115 t ha^{-1} can significantly reduce WF to about 43%. This research underscores the need for water-efficient practices to address potential water scarcity of the region, while emphasizing the limited water scarcity impact of bioethanol industry.

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Keywords: *water footprint, water footprint assessment, water scarcity, bioethanol sugarcane, Negros Occidental, Philippines*

INTRODUCTION

Water crisis, or the insufficiency of water supply due to rapidly growing population coupled with unsustainable water use and impacts of climate change, has long been a global challenge. In 2018, United Nations reported that over 2 billion people from different countries is experiencing water stress, and projections show that water stress and water scarcity will continue to intensify over the years.

One of the industries considered as a threat that may worsen water scarcity is biofuel – an alternative transportation fuel derived from biological sources which may be in the form of liquid fuel (e.g., bioethanol and biodiesel) or gaseous fuels (e.g., biogas and hydrogen) (*International Energy Agency 2004*). According to *Gerbens-Leenes et al.* (*2009b*), water footprint of energy from biomass is nearly 70 to 700 times larger than that of fossil fuels, and bulk of its water consumption can be regarded from the cultivation of biomass as feedstock for biofuel production. Bioethanol global average WF is at 2,855 L L^{-1} (*Gerbens-Leenes and Hoekstra 2009a*). The study of *Chiu et al.* (*2016*) reported that bioethanol WFs from various studies ranges from 790 L L^{-1} to 11,030.4 L L^{-1} bioethanol, wherein the lower end was obtained in a French sugar beets WF study while the upper range comes from molasses in Thailand. Notably, a more recent study by *Mekonnen et al.* (*2018*) suggests that US corn bioethanol has even lower water footprint of about 541 L L^{-1} bioethanol, while that of Brazilian sugarcane bioethanol is around 1,115 L L^{-1} bioethanol (considering only blue and green WF). For Brazilian sugarcane bioethanol, 66 L L^{-1} is attributed to total blue WF, comprising 17 L L^{-1} for bioethanol production stage and 49 L L^{-1} for total agricultural stage, while the rest is green WF.

The domestic biofuel industry in the Philippines is driven by the biofuel blending mandate under the Republic Act No. 9367, otherwise known as Biofuels Act of 2006. The law primarily aims to reduce the country's dependence to imported fossil fuels. For bioethanol alone, local capacity is about 380.5 MLPY or about 50% of the local bioethanol demand at 10% bioethanol blending (*DOE 2019*). In comparison to the global bioethanol production of approximately 111 billion liters in 2019, primarily led by the United States and Brazil, the contribution of Philippine bioethanol is only 0.34% of the total global bioethanol output. Bioethanol in the Philippines comes from sugarcane and molasses. Negros Occidental, being the top producing sugarcane province in the Philippines, is the second largest producer of bioethanol, next to Batangas, contributing to about 30.6% of the domestic bioethanol production.

The water footprint of bioethanol production in Negros Occidental and its contribution to the water demand in the region was assessed. The fresh water or "blue" water scarcity of its catchment was also evaluated. Water scarcity ranks among the foremost global environmental concerns. Evaluating strategies for sustainable development, such as promoting bioethanol production for energy sustainability, is imperative. It is crucial to assess whether these initiatives inadvertently contribute to the depletion of another vital resource- water. Moreover, process water footprint sustainability was also assessment to identify hotspots within the system boundary and recommend strategies towards bioethanol water footprint reductions.

MATERIALS AND METHODS

System Boundary and Case Scenarios

Water footprint accounting of bioethanol for this study covered cradle-to-gate analysis from feedstock cultivation up to processing of sugarcane or molasses in the distillery to produce bioethanol. System boundaries of the three case scenarios were considered (**Figure 1**).

The first case utilizes solely sugarcane as feedstock for bioethanol production, hence involving sugarcane cultivation in the field followed by bioethanol production in the distillery having sugarcane milling facility. The second case, on the other hand, is the system boundary of solely molasses bioethanol. Using molasses as feedstock for bioethanol production has an additional molasses production stage. Molasses is being produced as by-product of raw sugar production in the sugar mill. Lastly, the third case uses 50% sugarcane and 50% molasses to produce bioethanol. Therefore, combination of Case 1 and Case 2 system boundary is employed.

Functional Unit

Functional unit for water footprint (WF) accounting is on a liter per liter (L L^{-1}) bioethanol basis for the entire bioethanol production from feedstock to the bioethanol produced in the distillery. However, calculations are based on a 30 million liters per year (MLPY) bioethanol distillery capacity.

Data Collection

Water footprint accounting and sustainability assessment require a numerous amount of data to be executed. Data gathering in bioethanol processing plants, sugar mill and a sugarcane plantation test site was done from August 2018 to January 2020 in Negros Occidental. The selected sugarcane plantation test site was Calatrava, Negros Occidental and data gathering was done to determine cultivation practices and estimate sugarcane crop water requirement.

A questionnaire was developed to determine the crop characteristics, and environmental factors and management practices data on the selected test site,

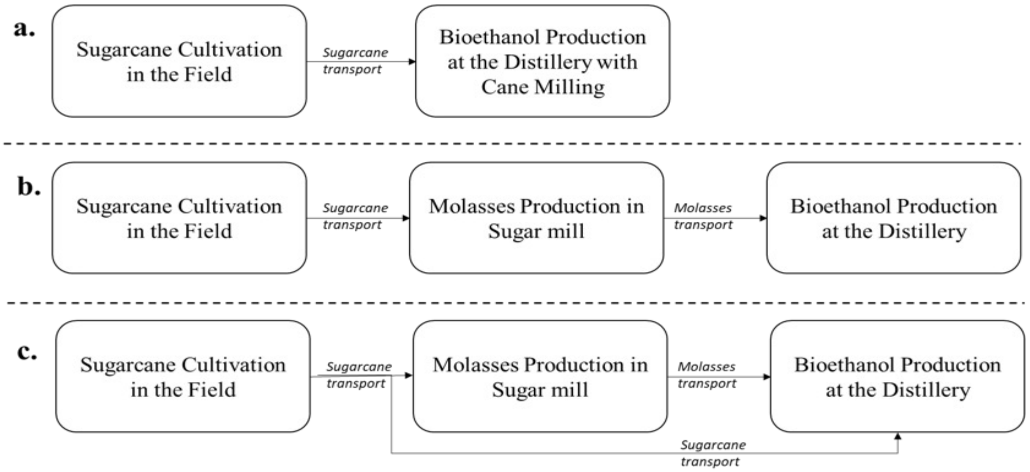

Figure 1. Case scenarios system boundary (a. Case 1-Sugarcane as Feedstock, b. Case 2 – Molasses as Feedstock, c. Case 3 – Sugarcane and Molasses as Feedstock) considered in the study.

location of sugarcane site was determined using GPS, while meteorological data was obtained from available weather data online (World Weather Online n.d).

A detailed process scheme, material and energy balance of a 30 million liters per year (MLPY) bioethanol plant was developed for this study based on the data gathered, through site visits, technical discussions, and key informant interviews, from the four bioethanol distilleries in Negros Occidental. Moreover, data gathering was also conducted in one sugar mill in the country to determine the production process and specifications of sugar production, wherein molasses is a co-product.

Water footprint accounting and sustainability of the catchment area required ground and surface water as well as natural run-off data. These data were obtained from the Department of Environmental and Natural Resources– National Water Resources Board (DENR-NWRB) of the Philippines.

Sugarcane Plantation Profile

The 128-ha farm assessed in Calatrava, Negros Occidental is situated in 07°06'34.4" north and 124°05'30.3" east. It has plain to slope topography with clay loam soil. The varieties used are VMC 86-550 (green cane) and VMC 88-354 (purple cane). The crops are planted in row pattern with standard planting distance of 1.5 m x 1.5 m. In a hectare, approximately 6,000 plants were established. Management practices include off-barring, pre-application of urea, di-ammonium phosphate (DAP) and muriate of potash (MoP) fertilizer during land preparation, fertilization of urea and MoP during growing to brushing (before harvesting) stage and application of herbicide for control of white grubs. Sources of water are spring water irrigation using overhead sprinklers or flooding after planting, while the rest of the crop growth stages rely on rainfall to irrigate the crop. Harvesting was done manually. First harvesting was on January 2018 wherein 82 t ha^{-1} were obtained. Ratooning was done twice before planting new crops. Waste was burnt after harvesting.

Water footprint accounting

The WF accounting can be subdivided into three major components– sugarcane cultivation in the field, molasses production in the sugar mill, and bioethanol production in the distillery (**Figure 1**). The scope of water footprint accounting of sugarcane cultivation in the field for this study begins with storing water to its use in the field (**Figure 2**).

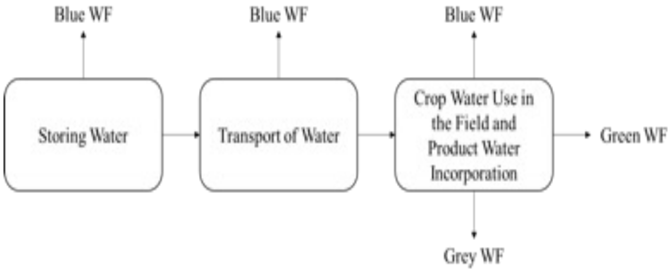

Figure 2. Growing crop water footprint accounting (*Hoekstra et al. 2011*).

The total WF of growing sugarcane crop is the summation of the water evaporated in transporting irrigation water to the field, crop water requirement for the entire cropping cycle and the water incorporated in products (**Figure 2**). Total WF can be subdivided into blue, green, and grey WFs. Equations used to calculate sugarcane crop's blue and green WFs, and grey WFs are shown in equations 1 and 2, respectively.

$$WF_{Proc,green\ or\ blue} = \frac{CWU_{green\ or\ blue}}{Y} \tag{1}$$

where CWU is the crop water use in m^3 ha^{-1} and Y is the crop yield (t ha^{-1}).

$$WF_{Proc,grey} = \frac{(\alpha XAR)/(C_{max} - C_{nat})}{Y} \tag{2}$$

where α is the leaching run-off fraction, AR is the chemical application rate in kg ha^{-1}, C_{max} is the maximum acceptable concentration in kg m^{-3}, Cnat is the natural concentration of the pollutant, and Y is the Crop Yield in ton ha^{-1}. Equivalent leaching run-off fractions of the calculated nitrogen application rates for urea and DAP are 0.078 and 0.07, respectively (*Chukalla et al. 2017*); while phosphorus application rate for DAP is 0.03 (*Franke and Matthews 2013*). Meanwhile, the maximum allowable nitrogen and phosphorus concentrations for Class C effluent or discharge in the country is 0.7 mg nitrate L^{-1} and 0.5 mg phosphate L^{-1}, respectively, (DENR Administrative Order 2016-08) and the natural nitrogen and phosphorus concentration is about 0.25 mg L^{-1} and 0.03 mg L^{-1}, respectively.

A water footprint calculator, developed by *Magadia et al.* (*n.d.*) (pending patent application) as one of the outputs of the Department of Agriculture – Bureau of Agricultural Research (DA-BAR) funded project "Sustainable Water Allocations and Management of Selected Agriculture Sector's Priority Crops through Water Footprint Assessment", was used to calculate sugarcane crop's WF in the studied test site. The calculator follows the FAO Penman-Monteith equation to estimate the reference crop evapotranspiration (ETo) (Equation 3). However, ETo only factors weather and other agro-climatic parameters at specific time and location where a crop is situated and cultivated, to account for the actual crop evapotranspiration (ETc), crop factor (Kc) must be determined and varies mainly on crop type, variety, developmental stages, resistance to transpiration, crop height and roughness, reflection, ground cover and crop rooting characteristics. Procedure in calculating ETc can be seen in *UN FAO Crop Evapotranspiration* (*1998*). Moreover, a water footprint calculator was used to calculate sugarcane crop's WF in the studied test site.

$$ET_O = \frac{0.408\Delta\,(R_N - G) + \gamma\frac{900}{T+273}u_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \tag{3}$$

Where ETo is the reference evapotranspiration [mm d^{-1}], Rn is the net radiation at the crop surface [MJ m^{-2} d^{-1}], G is the soil heat flux density [MJ m^{-2} d^{-1}], T is the mean daily air temperature at 2 m height [°C], u_2 is the wind speed at 2 m height [m s^{-1}], e_s is the saturation vapour pressure [kPa], e_a is the actual vapour pressure [kPa], e_s - e_a is the saturation vapor pressure deficit [kPa], Δ is the slope vapour pressure curve [kPa $°C^{-1}$], and γ is the psychrometric constant [kPa $°C^{-1}$].

Water footprint of bioethanol is calculated by considering the water consumption and water pollution in all steps of the production chain. Since bioethanol production in the distillery produces several co-products (i.e., filter mud, liquid CO_2, biogas and electricity), the stepwise accumulative approach was applied for this study. This approach determines the total water footprint within the system and allocate this WF to each product based on the product fraction (or the quantity of the product obtained per quantity of input materials), and based on the value fraction of the output products (or the ratio of market value of this product to the aggregated market value of all the output products obtained from the input materials).

Material and energy balances were conducted from the data gathered in the bioethanol plants to design a 30 MLPY bioethanol plant and a sugar mill that can cater the molasses requirement of the bioethanol plant for all three cases considered in this study.

Water balances for bioethanol plant and sugar mill were, then, conducted to determine the individual addends in equation 4 to compute for the blue WF of the process.

$$WF_{proc,blue} = \mathit{Blue\ Water\ Evaporation} + \mathit{Blue\ Water\ Incorporation} + \mathit{Lost\ Return\ flow} \tag{4}$$

Pollutant flowrate and concentrations of treated or untreated wastewater generated from the system that are being brought back to the catchment must be considered for grey water footprint calculation. The equation used for grey water footprint of a process is shown in Equation 5.

$$WF_{proc,grey} = \frac{L}{C_{max} - C_{nat}} \tag{5}$$

where L is the wastewater flowrate, C_{max} is the effluent concentration, and Cnat is the natural concentration in the direct catchment.

Water footprint sensitivity analysis

A sensitivity analysis was performed to investigate the effect of increasing or decreasing sugarcane yield to the overall water footprint of bioethanol production. The sugarcane yields considered in the study are as follows: 40 t ha^{-1}, 65 t ha^{-1} (*SRA 2016*), 82 t ha^{-1} (sugarcane yield of test site), and 115 t ha^{-1}.

Water footprint sustainability assessment

There are two parts of the water footprint sustainability assessments. The first part investigated the hotspots and unsustainable processes or steps over the entire bioethanol production supply chain from cradle to gate. The second part of the assessment covered the "environmental geographic sustainability" where the bioethanol distilleries are located by assessing the sustainability of their catchment areas.

For the environmental sustainability assessment, water scarcity of the catchment area was investigated. This study focused on the blue water scarcity of the catchment, which is the summation of blue water footprint within the catchment over the available water in the catchment (see Equation 5). A blue water scarcity of 100% depicts that the available blue water has been fully consumed. Water scarcity thresholds ranging from low to severe were used in the study (**Table 1**).

$$WS_{blue}[x,t] = \frac{\sum WF_{blue}[x,t]}{WA_{blue}[x,t]} \tag{6}$$

where WS_{blue} is the blue water scarcity, WF_{blue} is the total blue water footprint in the catchment, and WA_{blue} is the available water in the catchment.

Scenario analysis was also conducted to determine the impact of bioethanol industry to the sustainability of its catchment area at present up to 2030 and the effect of water footprint reduction of bioethanol production to the catchment at present up to 2030.

Table 1. Water scarcity thresholds (*Chouchane 2015*).

Blue water scarcity levels	Water scarcity thresholds
Low blue water scarcity	< 20%
Moderate blue water scarcity	20-30%
Significant water scarcity	30-40%
Severe water scarcity	>40%

Water Footprint Response Formulation

The last part of any water footprint assessment is formulating responses or action plans upon assessing and weighing the impacts of a product, activity or development. For this study, two sets of responses were expected. The first set involved the water consumption and water pollution reduction strategies and/or technologies to make the entire bioethanol production process sustainable. The second set of responses involved strategies that would environmentally sustain the limited water resource.

RESULTS AND DISCUSSION

Water Footprint of Sugarcane Production in Negros Occidental

Water footprint accounting is done based on the feedstock and hectarage requirements of the three cases under study for a 30 MLPY bioethanol production, wherein the sugarcane yield is 82 t ha^{-1} (test site yield), molasses yield in the sugar mill is 40 t-cane^{-1} and assumed reference bioethanol yield is 70 L t-cane^{-1} and 245 L t-molasses^{-1}.

Green WF has the largest WF contribution of about 65.5% (**Table 2**). This is attributed to the estimated crop water use of the sugarcane crops (following the UN FAO Crop Evapotranspiration guidelines) of about 197 m^3 t-cane^{-1} (16,116 m^3 ha^{-1}) wherein 99% of which is from green WF while the remaining 1% is from blue WF. Blue WF has minimal contribution since irrigation is only being employed during planting. The green-blue WF value estimated for the study site is the same as the global average green-blue WF reported by *Mekonnen and Hoekstra* (*2014*). Meanwhile, grey WF attributed to fertilizer use leaching or run-off contributes to about 34% of the total WF of sugarcane crops.

Based on the data gathered on-site, about 200 kg of Urea is applied twice per cropping and 200 kg of Di-ammonium Phosphate (DAP) is applied once per cropping. These fertilizer application rates translate to about 92 kg N ha^{-1} for Urea, and 36 kg N ha^{-1} and 92 kg P ha^{-1} for DAP. Based on these fertilizer application rates, the calculated grey water footprint is 102 m^3 t-cane^{-1} (8,351.73 m^3 ha^{-1}).

The two other components, water incorporated in cane and water evaporated due to transport and storage, has also negligible WF contribution (**Table 2**). Note that mature sugarcane stalks have about 71.5% water content, and for every ton of sugarcane stalk harvested, about 5% is considered as trash. These are average data from key informant interviews with sugar mills in the country. Evaporated water due to storage and transport, on the other hand, is assumed to be at 10%.

The equivalent total WFs of Cases 1, 2 and 3 for a 30 MLPY bioethanol production capacity are 128.3 Mm^3, 909 Mm^3 and 518 Mm^3, respectively (**Table 2**). Due to higher sugarcane requirement to produce the needed molasses for bioethanol production than directly using sugarcane as feedstock for bioethanol production, Case 2 has the highest water footprint, followed by Case 3 at 43% difference, while Case 1 has the lowest WF or 86% lower than Case 2.

Water footprint of a typical sugar mill in the Philippines

Assumptions and basic plant data of sugar factory operations are applied or derived from material and energy balances of the two cases (Case 2 and 3), which were used in the water balance calculations were based on different parameters (**Table 3**).

Water balance revealed that water coming in and out of the sugar mill is about 12,409 m^3 d^{-1} for Case 1 and halved for Case 2. About 97% of this water is from the water incorporated in cane stalks. The remaining

Table 2. Calculated individual green, blue and grey WF of each component making up to the WF of sugarcane crop production in the field.

Components	Green WF	Blue WF	Gray WF	Total WF
	m^3 t-cane^{-1}	m^3 t-cane^{-1}	m^3 t-cane^{-1}	m^3 t-cane^{-1}
Crop Water Use	195.43	1.11	101.85	298.39
Water Incorporated in Cane Stalks	0.64	0.04		0.68
Transport of Water		0.12		0.12
TOTAL	196.07	1.27	101.85	299.19

Table 3. Basic production specifications of sugar mills considered in the study for cases 2 and 3.

Parameters	Case 2	Case 3
Capacity, t-cane d^{-1}	16,870	8,435
No. of Days	180	180
% Bagasse in cane	28	28
Electricity Generation, MW	77.3	38.7
Raw Sugar Production, t d^{-1}	1,808	911
Final Molasses Production, t d^{-1}	698	352

3% comes from wash water and make-up water requirement of the plant. However, it is important to mention that during start-up, the water requirement is fifty-one times higher than the daily operation requirement equivalent to 17,582 m^3 d^{-1} for Case 2 and 8,791 m^3 d^{-1} for Case 3. This is due to water and steam recycling within the system during regular operation. Furthermore, water balance calculations determined the rate of water evaporation from the system and water incorporated in molasses making up the blue WF of molasses as co-product of sugar milling (**Table 4**).

Evaporation within the system comes from evaporation losses during cane milling, flue gas water composition from the boiler in the co-generation unit, evaporation and drift loss from spray pond and cooling towers, and evaporation from the pan-boiling, crystallization and centrifugation unit. This contributed to the largest WF attributed in molasses from sugar milling, (**Table 4**), of about 913 L t-molasses^{-1}. Meanwhile, water incorporated in molasses was derived based on the percent water composition of molasses of about 22% and molasses yield of the system from material balance calculations.

The figures shown reflect the WFs attributed or allocated to molasses (**Table 4**). An allocation factor equivalent to 0.12 for molasses was calculated based on economic allocation wherein production amounts and prices of the three co-products (excess electricity, raw sugar, and molasses) were determined. This figure means that 12% of the water footprint from sugar mill is attributed to molasses.

Table 4. Summary of blue (and its components) and grey water footprint attributed to molasses for Cases 2 and 3 in L t-molasses^{-1}.

Components	Cases 2 and 3
	L t-molasses^{-1}
Water Evaporation	913.44
Water Incorporated	220.00
$\text{Blue WF}_{\text{molasses from mill}}$	1,133.44
$\text{Grey WF}_{\text{molasses}}$	1.84
$\text{Total WF}_{\text{molasses}}$	1,135.28

In comparison to a similar study conducted in Thailand, the total water footprint calculated in this study for a raw sugar factory, approximately 2.31 L kg^{-1} of raw sugar, is notably 61.5% lower than Thailand's total water footprint for raw sugar, which stands at 6 L kg^{-1} (covering juice extraction to raw sugar processing). Also, raw sugar WF constitutes to about 74.5% of the total refined sugar production WF of 8.12 L kg^{-1} (*Suwanwaree et. al 2015*). Lower water footprint of sugar mill may be attributed to efficient steam and water recycling within the system.

Water footprint of bioethanol distilleries

Similar with the methodology done in sugar mill, material and energy balance were conducted to determine the parameters, inputs and, outputs of bioethanol production for a 30 MLPY bioethanol plant.

Since Case 2, or solely using molasses for bioethanol production, does not have bagasse to produce power for the plant's own power requirement, coal is used as substitute (**Table 5**).

Water evaporation, sharing the majority of the WF accounted for all cases in the distillery, was obtained from water balance calculations (**Table 6**). This comes from milling, boiler blowdown and flue gas, evaporation and drift loss from spray ponds and cooling towers, and from evaporation Furthermore, water balance revealed that water requirement of the distillery of about 40,300 m^3 d^{-1}, 43,600 m^3 d^{-1}, 42,000 m^3 d^{-1} for Case 1,2, and 3, respectively, will significantly lower by 107 times due to water and steam recycling practices within the system. This water requirement includes additional boiler feedwater, wash water, cooling tower make-up water, dilution water, and scrubber make-up water.

Water incorporated in bioethanol is negligible since bioethanol water content is only about 0.06% (**Table 6**). On the other hand, no direct grey WF is accounted since

Table 5. Basic specifications of bioethanol production operations for Cases 1 to 3.

Parameters	Case 1	Case 2	Case 3
Bioethanol Capacity, kL d^{-1}	107	107	107
No. of Days	280	280	280
% Bagasse in cane	28	N/A	28
Coal Usage for Co-gen, t d^{-1}	N/A	145.6	N/A
Electricity Generation, MW	8	2.3	4.5
CO_2 Production, t-d^{-1}	48	48	48
Fertigation, t-d^{-1}	807	1,415	1,112

Table 6. Total direct and indirect blue and grey water footprints attributed to bioethanol in the distillery for Cases 1, 2 and 3.

Components	Case 1	Case 2	Case 3
	(L L^{-1})	(L L^{-1})	(L L^{-1})
Direct Blue WF			
Water Evaporation	27.98	32.97	33.18
Water Incorporated	0.00	0.00	0.00
Total Direct Blue WF	27.98	32.98	33.18
Indirect Blue WF			
Coal		0.56	
Transport of Coal		0.15	
Total Indirect Blue WF		0.71	
Total Blue WF	27.98	33.69	33.18
Indirect Grey WF coal		1.69	
Total WF	27.98	35.38	33.18

huge wastewater from distillation or distillery slops of the plant is treated in an anaerobic digestion to produce biogas for additional electricity generation, wherein the resulting effluent is utilized as liquid fertilizer or fertigation back to the sugarcane crops (**Table 6**).

Economic allocation factors computed to arrive with the values are 0.84, 0.94, and 0.91 for Case 1, 2, and 3, respectively (**Table 6**). Products considered for allocation are excess electricity generation, liquid CO_2, and bioethanol. Note, however, that Case 2 does not have excess electricity generation as it is only generating its own plant capacity.

Indirect blue and grey WFs of using coal to produce the distillery's own power requirement were also reflected for Case 2 (**Table 6**). Based on the study of *Zhu et al.* (*2020*), water footprint of coal is about 3.3 m^3 MWh^{-1}, and 25.9% of which is attributed to coal mining and washing, wherein 24.8% is blue WF while the remaining 75.2% is grey WF. These data were used in the calculations of indirect WF of coal. Meanwhile, blue WF due to transport of coal was calculated based on the water footprint coefficient of diesel equivalent to 0.0134 m^3 kg^{-1} (*Rossi et al. 2019*), fuel economy of 1.92 km L^{-1} for a 20-ton capacity truck, and distance of 460 km between Semirara Island and Negros Occidental.

Indirect blue WF from coal contributes to about 2.1% of the total blue water footprint while the total WF due to coal use (total blue and grey WF) is 2.40 L L^{-1} of bioethanol or 7% of the total WF of the bioethanol processing plant (**Table 6**). Contribution of indirect WF from coal further increases total WF of Case 2, other than the fact that water evaporation of Cases 2 and 3 are higher than Case 1.

Case 2 has the highest total water footprint within the distillery of about 35.38 L L^{-1} bioethanol, followed by Case 3 (34.03 L L^{-1} bioethanol); while Case 1 has the lowest total water footprint of about 27.98 L L^{-1} bioethanol among the three. On the average, the total WF attributed to bioethanol in the distillery is 34.46 L L^{-1} bioethanol.

Total WF of bioethanol production

The component water footprints making up the total water footprint of producing a liter of bioethanol in Negros Occidental, Philippines was outlined (**Table 7**) based on the system boundary for the three cases under study (**Figure 1**).

WFs of components are the results of individual WF accounting discussed in the previous sections for a designed 30 MLPY capacity bioethanol production. Indirect WFs due to transporting raw materials (**Table 7**)(e.g. sugarcanes to the sugar mill or to the bioethanol plant, and molasses to the bioethanol plant), on the other hand, was calculated based on the determined feedstock requirements of both the sugar mill and bioethanol plant for the three cases under study. It was assumed that a diesel-powered 20-t capacity truck with 1.92 km L^{-1} fuel economy traveling a distance of 50 km was used to transport both sugarcane and molasses. Water footprint of diesel is 0.0134 m^3 kg^{-1} (*Rossi et. al 2019*).

The total WFs for cases 1, 2 and 3 are 4,292.85 L L^{-1}, 3,574.28 L L^{-1}, and 3,935.06 L L^{-1} or an average total WF of 3,934.06 L L^{-1} bioethanol (**Table 7**). These figures suggest that using molasses for bioethanol production is favorable compared to using sugarcane, in terms of their water footprints. The quantified WF of bioethanol in Negros Occidental is 38% higher than the reported global average WF of bioethanol of 2,855 L L^{-1} by *Gerbens-Leenes and Hoekstra* (*2009*). The higher WF is attributed to

Table 7. Total water footprint of bioethanol production and the water footprint of its life cycle components for Cases 1, 2 and 3.

Life Cycle Components	Case 1	Case 2	Case 3
	(L L^{-1})		
Plantation	4,264.45	3,531.08	3,897.77
Transport of Cane Stalks to Sugarmill or Bioethanol Plant	0.41	2.94	1.68
Sugarmill (molasses)		4.75	2.38
Transport of Molasses to Bioethanol Plant		0.12	0.06
Bioethanol Plant	27.98	35.38	33.18
TOTAL Water Footprint	4,292.85	3,574.28	3,935.06

the significant contribution of grey WF in the sugarcane plantation, stemming from the extensive use of inorganic fertilizers. Although it is important to note that this assessment does not represent the WFs of sugarcane and bioethanol production in Negros Occidental. The analysis is based on agronomic, agroclimatic data and cultural practices from a single farm in Negros Occidental, limiting the broader generalization of the findings.

Sugarcane plantations makes up the majority (98.6-99.1%) of the water footprint of producing bioethanol. Crop water requirement in the field far outweighs the WFs of sugarcane and/or molasses processing and deliveries to produce bioethanol. Case 2, or bioethanol using molasses, has the lowest WF since economic allocation done from sugarcane plantation to sugar mill to produce molasses suggests that only 12% of the total water footprint of raw sugar production is allocated to molasses. On the contrary, Case 2 has the highest WFs in bioethanol processing while Case 1 has the lowest.

Bioethanol production in the bioethanol distillery, and molasses production in the sugar mill for Cases 2 and 3 have a very minimal WF share of about 0.9-1.2%, and 0.1-0.2%. Water footprints due to raw materials hauling have negligible percent contribution to the total water footprint due to the very large water footprint in the sugarcane field.

In terms of comparing the blue, green, and grey WFs of the three cases under study, green WF has the largest contribution of about 65.5% to the total WFs f(**Figure 3**). For this study, green WF is only attributed to the rainfall availability and water requirement of equivalent sugarcane plantation to produce a liter of bioethanol. Grey WF follows green WF for the next largest contribution of about 34.1%, while blue WF has a very minimal share of only about 0.4%. Grey WF is attributed to the fertilizer use in the field, and very minimal contribution from coal use in bioethanol plant for Case 2 and treated wastewater in sugar mill for Cases 2 and 3. Blue WFs are distributed to all components of bioethanol production. Note that since minimal irrigation is practiced in the sugarcane test site visited (which is the case for most sugarcane plantations in the country), blue WF contribution in sugarcane plantation is insignificant.

Bioethanol Water Footprint Sensitivity Analysis at Varying Sugarcane Yields

Since majority of WF of bioethanol is from sugarcane cultivation, a sensitivity analysis was made to investigate the effect of increasing or decreasing sugarcane yields to the overall WF of bioethanol. For this study, cane yields of 40, 65, 82 and 115 t ha^{-1} are analyzed for bioethanol WF sensitivity. Forty tons per hectare represents the lowest sugarcane yield, 65 t ha^{-1} is the average sugarcane yield in 2017 (*SRA n.d.*), 82 t ha^{-1} is the yield of the sugarcane farm assessed in this study, and lastly 115 t ha^{-1} represents the highest sugarcane yield.

For all cases, it can be observed that as cane yield decreases, the total WF of bioethanol significantly increases. In the same way, as cane yield increases,the bioethanol WF decreases (**Table 8**). This trend is observed

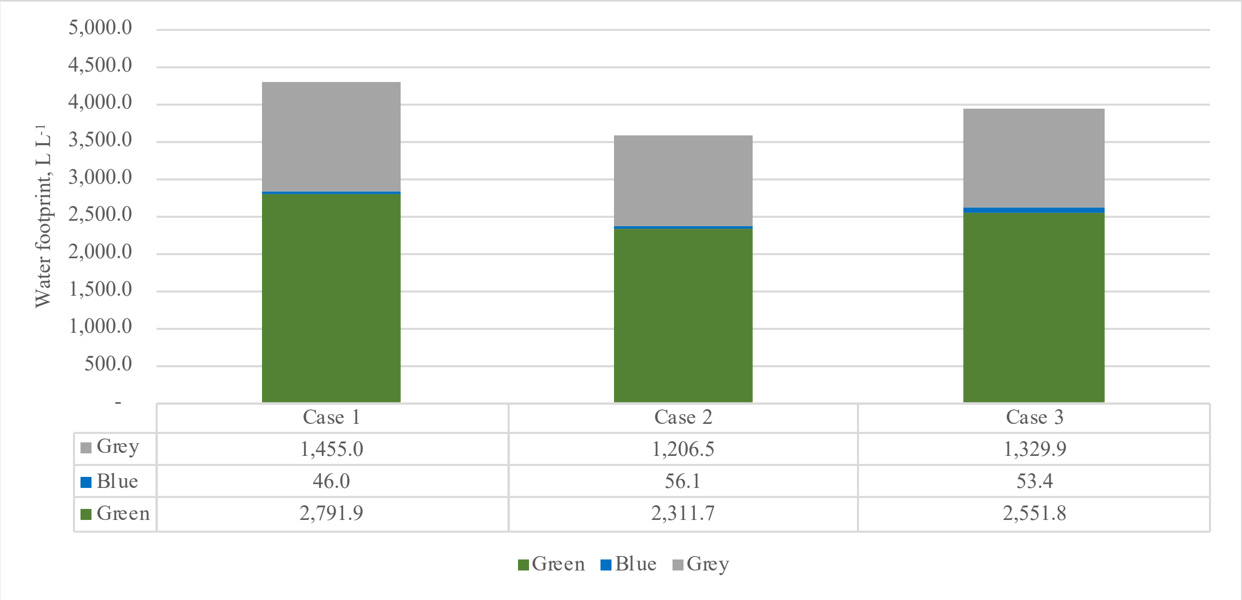

Figure 3. Comparison of green, blue and grey Water Footprints to the total Water Footprints of Cases 1 to 3 in L L^{-1}.

Table 8. Effects to total Water Footprints of bioethanol at varying sugarcane yields.

Cane Yield	Total Water Footprint of Bioethanol		
	Case 1	Case 2	Case 3
(t ha^{-1})	(L L^{-1})	(L L^{-1})	(L L^{-1})
40	8,770.52	7,281.91	8,027.72
65	5,408.17	4,497.79	4,954.48
82	4,332.58	3,623.05	3,979.31
115	3,069.14	2,561.01	2,816.57

since higher sugarcane yield means lower hectarage requirement, therefore, lower WF due to sugarcane cultivation. Since majority of total WF of bioethanol is attributed to sugarcane growing in the field, lower sugarcane WF greatly affects the total WF of bioethanol. Lower sugarcane yield means higher hectarage requirement resulting to higher WF of sugarcane, and therefore, higher total WF of bioethanol.

Total Water Footprint of Bioethanol in Negros Occidental

Given that the current bioethanol capacity in Negros Occidental is 116.5 MLPY or 30.6% of the total bioethanol production in the country, wherein 40 MLPY or 34% follows the Case 1 WF calculated in the study while the rest is applicable for Case 2 WF results. The total WF of the current bioethanol production in Negros Occidental is 560.41 mega cubic meter (MCM) (**Table 9**).

Process Water Footprint Sustainability Assessment

Results of water footprint accounting, in general, suggests the use of molasses for bioethanol production since water footprint from sugarcane plantation to raw sugar production produces other co-products (i.e., raw sugar, molasses, electricity). This allocates the calculated total WF up to raw sugar production to these products, thereby reducing the WF attributed to molasses for bioethanol production. However, looking closely to the water footprint of individual components may suggest unsustainable WF since other possibilities can be explored to lower the WF of that given component. The following sections present the results of the WF sustainability assessment conducted for the three major components of bioethanol WF.

Table 9. Total water footprint of bioethanol production in Negros Occidental.

Cases	Green WF	Blue WF	Gray WF	Total WF
	(MCM)	(MCM)	(MCM)	(MCM)
1	140.88	2.02	73.42	216.33
2	223.10	4.58	116.40	344.08
1+2	363.98	6.60	189.82	560.41

Sugarcane Cultivation in the Field. Since variation in sugarcane yield greatly affects the water footprint of bioethanol, sensitivity analysis suggests that increasing the sugarcane yield would significantly reduce WF in the plantation. Another huge component of sugarcane cultivation WF is the fertilizer used in the field, which translates to the grey WF. However, to increase the efficiency of sugarcane, one of the options is to increase fertilizer use. Therefore, a separate study must determine which combination of fertilizer, sugarcane yield, and other sugarcane yield-increasing practices must be adapted to result to a minimized sugarcane production WF in the field.

The WF of sugarcane in this study is about 300 m^3 t-$cane^{-1}$. For a similar study in Thailand and Brazil, average WF is only about 202 m^3 t-$cane^{-1}$ (*Kongboon and Sampattagul 2012*) and 201 m^3 t-$cane^{-1}$ (*Scarpare et. al 2015*), respectively. Therefore, it can be deduced that since WF of sugarcane from the study is higher than the similar studies from other countries, sugarcane WF in Negros Occidental is considered unsustainable and can further be minimized to make more sustainable.

Molasses Production in the Sugar Mill. Raw sugar production practices in the Philippines have significantly lower WF compared to the raw sugar water footprint in Thailand (*Suwanwaree et al. 2015*). This is probably because of the efficient steam and water recycling within the system. However, there could still be improvements within the system such as exploring the use of wastewater of about 5,130 m^3 d^{-1} for other purposes or treat it further such that the effluent concentration is comparable with that of the natural concentration of the immediate catchment. In addition, there is excess exhaust steam from co-generation of about 656 m^3 d^{-1} that does not undergo any heat recovery and are directly being condensed so as not to be evaporated. This excess exhaust steam could still be used to other production processes to achieve circular economy. Hence, raw sugar production WF is still considered unsustainable.

Bioethanol Production in the Bioethanol Distillery. Although most of the water coming out of the system are either being recycled back within the system (i.e., as imbibition water, boiler feed water, filter wash water, make-up water, dilution water, etc.), alternative sources of the remaining high water requirement for the make-up water (2,67.87 m^3 d^{-1}) of distillation column's condenser cooling water as well as significant dilution water requirement

(720.35 m^3 d^{-1}) of feedstock prior to fermentation must be explored. Circular economy concept must be applied such that output water of one industry could be used to supply the make-up water and dilution water of the bioethanol plant. Moreover, even though exiting steam from distillation and heaters are being condensed to be used for other water requirement of the system, the heat from those steam could have been further used as heat source to unit operations, therefore is considered as waste heat. With these potential modifications and water minimization options, WF of bioethanol production in the distillery is considered unsustainable. However, it is important to mention that putting good use of the large volume of wastewater or distillery slops to recover valuable product such as methane (CH_4) for power generation and as fertigation back to sugarcane fields are innovative measures to considerably minimize water footprint of the distillery.

Geographic Sustainability of the Catchment

The catchment considered in this study is the catchment of the entire Western Visayas Region or Region VI. The region comprises Negros Occidental, sub-province of Guimaras, and the Panay Island covering a total area of 20,200 km^2. There are three major river basins in the Western Visayas Region. These include the Panay River basin in Capiz, the Jalaud River Basin in Iloilo, and the Ilog-Hilabangan River Basin in Negros Occidental. The average natural off from this region originating from these three basins is 47 MCM d^{-1} (*NWRB 1976*).

Geographic environmental sustainability assessment, in terms of blue water scarcity (WSblue) and water pollution level (WPL), was done for this study based on the available data for this catchment from NWRB.

Blue Water Scarcity. Given that in 2018, the water demand in Region VI is about 6,274 mega cubic meter (MCM) and the total water potential (from ground water and 80% dependable surface water) is around 15,341 MCM, the calculated WSblue of the region is 40.9% (*NWRB, pers comm. December 2018*). The figure can be interpreted as “40% of the water potential in the region is being used up at present”. However, a water scarcity threshold greater than 40% means that the catchment is experiencing sever water scarcity (**Table 1**).

Contribution of the bioethanol industry to the total water demand of the region is only about 0.1%. This is based on the actual bioethanol production of the region of about 116.5 MLPY (30.6% of the total bioethanol production), 34% of which practices Case 1 while the rest are practicing Case 2. Therefore, at present, bioethanol industry in the region does not cause any alarm to the scarcity of the total water resource of the region.

Water Pollution Level. Since there were no data obtained from other sources or industries contributing to the total grey water footprint of the catchment, this section only examined the percentage of the grey water footprint of bioethanol to the total natural run-off.

Percentage of grey water footprint or WPL of the present bioethanol industry capacity equivalent to 189 MCM y^{-1} or 0.68 MCM d^{-1} to the total natural run-off of 47 MCM d^{-1} is about 1.4%. However, there are other major water pollution contributing sectors or industries that need to be assessed to look at the state of the WPL in the region.

Scenario Analysis

Based on the annual average increase of water demand and water potential decline of about 5.3% and 3.7%, respectively, for the period 1988 to 1994, annual blue water scarcity is assessed within a 12-year period (*PSA 2016*).

By 2028, water demand will use up all the available water during that period in Region VI starting the said year (**Table 10**). Meanwhile, the estimated equivalent blue water demand of bioethanol production in Region VI in 2030 is about 87.96 MCM or 0.75% of the total water demand during that year. Estimation of bioethanol demand is based on the 10% mandated bioethanol blending to gasoline, wherein the gasoline demand in 2030 is projected to be 15,518.58 ML (*DOE 2019*). Meanwhile, bioethanol share of Region VI to the total bioethanol capacity of the Philippines is assumed to be constant at 30.6%.

Water Footprint Response Formulation

Based on the findings of the study, several water footprint responses are suggested towards a more sustainable bioethanol production in Negros Occidental and its catchment. To attain lower WF of bioethanol production, the following are suggested:

1. Intensify research and development on high-yielding and drought-resistant sugarcane variety to increase sugarcane yield per hectare and thereby significantly lowering the WF of bioethanol production.

Table 10. Projected water demand, water availability and the equivalent water scarcity index from 2018-2030.

Year	Water Demand	Water Available	WS_{blue}
	MCM	MCM	%
2018	6,274.32	15,341.00	40.90
2019	6,606.86	14,773.38	44.72
2020	6,957.02	14,226.77	48.90
2021	7,325.74	13,700.38	53.47
2022	7,714.01	13,193.46	58.47
2023	8,122.85	12,705.31	63.93
2024	8,553.36	12,235.21	69.91
2025	9,006.69	11,782.51	76.44
2026	9,484.05	11,346.55	83.59
2027	9,986.70	10,926.73	91.40
2028	10,516.00	10,522.44	99.94
2029	11,073.34	10,133.11	109.28
2030	11,660.23	9,758.19	119.49

2. Optimize fertilizer use in the sugarcane farms to determine minimum fertilizer input requirement (lower grey WF) to achieve optimum sugarcane yield.
3. Develop irrigation scheduling not only to avoid water stress and increase sugarcane yield but also to optimize blue water footprint in the farm.
4. Determine other uses of wastewater from sugar mills
5. Optimize water and heat recovery within the two processing plants (sugar mill and bioethanol) and explore the possibility of these two plants or any other industrial plants to be adjacent with each other such that waste heat or water from one plant could be a valuable input to another (circular economy).
6. Increase sugar mill and bioethanol plant's process efficiency.

For the Region VI catchment, although water scarcity is not yet experienced at present and that bioethanol water requirement constitutes to a minimal percentage of water demand in the region, projection on the geographic sustainability of the catchment suggests that there is an impending threat on water scarcity in the region by 2028 provided that the assumptions used for this study are valid. Therefore, this study suggests the following to avoid such threat:

1. Develop plans and programs to minimize water use, especially of the major water consumers in the region; adopt water quality and quantity management plan
2. Allocate available water proportionally to the stakeholders.
3. Conduct economic valuation to determine payment of environmental services that can be used for watershed rehabilitation and other water quality and quantity management programs. This can serve as basis in pricing wastewater discharge penalty. Economic valuation can also be used to recommend action plans to water pollution challenges by comparing costs of different options, e.g., cost of pollution with abatement, cost of treatment by dilution or how many quantity of freshwater is necessary to dilute the concentration of pollutants present in the water, or cost no action.
4. Implement information, education, and communication campaign to educate stakeholders the importance of water and the potential outcomes of not reducing, re-using, or conserving their water use.
5. Location of bioethanol plants must be strategically planned such that available water and rate of water consumption will not deem the water catchment in the area unsustainable.

CONCLUSION

Water footprint accounting of bioethanol production in Negros Occidental, Philippines suggests that the total WFs of Cases 1, 2 and 3 bioethanol production equivalent to 4,293 L L^{-1}, 3,574 L L^{-1} (lowest), and 3,953 L L^{-1}, respectively, suggests that bioethanol production is not a threat to freshwater scarcity as it contributes to only 0.1% of the total water demand in the region. However, severe water scarcity is being experienced in the region at 40.9% water scarcity threshold in 2018. When projection was done up to 2030, it was found out that by 2028, water available in the catchment will be used up by the water demand of the stakeholders within the catchment and thereby posing a serious threat to water scarcity.

Investigating the WFs of individual components reveal that sugarcane cultivation in the field accounts for the majority (about 99%) of the total WF for all cases, and green WF has the highest share of about 64.8% of the total WF, followed by grey WF at 33.8%, and blue at 1.3% of the total WF. Since sugarcane cultivation has the highest WF among the components of bioethanol production, a sensitivity analysis was conducted to determine the extent of WF from plantation at varying sugarcane yield. Results showed that total average WF for the three cases can go as high as 8,027 L L^{-1} for a 40 t ha^{-1} or as low as 2,816 L L^{-1} for a 115 t ha^{-1} sugarcane yield. But based on the average sugarcane yield of 65 t ha^{-1} bioethanol production and characteristics in Negros Occidental, the total WF of bioethanol production in Negros Occidental was computed as 560.4 MCM y^{-1}.

Water footprint sustainability within the process infers that bioethanol production in Negros Occidental is considered unsustainable since improvements can still be made to lower the WF of the process. However, it is important to note that commendable water footprint strategies are in place that significantly reduces WF of the industry.

The findings from the study were used to come up with strategies to reduce the WF of the bioethanol industry in Negros Occidental and avoid the imminent threat of water scarcity in the region. In general, the study suggests increasing sugarcane yield through the development of high-yielding variety and irrigation scheduling and optimize the use of fertilizer in the farm to minimize grey water footprint at optimized sugarcane yield. For the production process, it is recommended to optimize process efficiency, recover waste heat and wastewater for other purposes, and practice circular economy. Meanwhile, the threat in water scarcity within the catchment must be planned out and programs must be developed to minimize water use and water pollution level. Proper allocation of available water, economic valuation of water within the region, and effective IEC campaign must also be done to prevent such threat. Moreover, location of bioethanol plants in the country must be strategically planned so as not to significantly contribute to water scarcity or water pollution level of a region or specific location.

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