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Determination of Environmental Impacts using Life Cycle Assessment of Plants Grown for Bioenergy: Example of Sorghum x Sudan Grass Hybrid

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ABSTRACT

Renewable energy sources are the most effective and cheapest method for combating climate change. Biomass, which is one of the renewable energy sources, is also one of the raw materials for biofuels. Sorghum x Sudan grass hybrid, which is drought tolerant and has a short vegetation period, is a biomass source. This study was carried out to determine the ethanol yield of sorghum x Sudan grass hybrid plants grown in an area with a semi-humid climate and to determine the environmental impacts of biomass. Environmental impacts were assessed using the life cycle assessment method. Environmental impact categories are divided into 11 categories according to the CML-IA Baseline model. As a result, the biomass yield was 49888 kg ha^{-1} and the ethanol yield was 1674.1 l ha^{-1}. According to the life cycle impact category of sorghum x Sudan grass hybrid biomass production, the highest environmental impact was 79.21%, causing marine aquatic ecotoxicity. According to the life cycle interpretation, it caused a global effect with a rate of 83.87%. In addition, the global warming value was calculated as 0.195 kg CO_2-eq $kg_{biomass}^{-1}$ (9728.16 kg CO_2-eq ha^{-1}). The agricultural phases with the most negative impact on the environment are irrigation and fertilization.

Keywords: Global warming, Climate change, Energy crops, Biofuels, Bioethanol

1. Introduction

With rapid population growth and industrial progress, energy use in the world is also increasing. According to data from 2018, the amount of energy used in the world was calculated as 14.4 billion tons of oil equivalent. This energy comes from fossil fuels (oil, coal, natural gas, etc.) at rates of 81.1% and renewable energy sources at 18.9%. Biomass constitutes 67.5% of energy obtained from renewable energy sources. In Türkiye, the amount of energy used was calculated as 147.5 million tons of oil equivalent. Within this energy, fossil fuels provide 86.2% (44.2 million TOE of coal, 41.9 million TOE of oil and 41.0 million TOE of natural gas) and renewable energy sources provide 13.8%. Biomass constitutes 15.5% of energy obtained from renewable energy sources (IEA 2021).

Biomass is a renewable energy source obtained from plants, agricultural wastes, animal wastes and urban solid wastes with important advantages such as being clean, easily available, sustainable and environmentally friendly. Biofuels obtained from biomass are organic (bioethanol, biodiesel, biogas, biomethanol, biohydrogen) fuels derived from living organisms and obtained from carbon-based products. These fuels significantly contribute to reducing fossil fuel consumption and greenhouse gas (GHG) emissions (Eren & Öztürk 2021).

Biofuel production must be environmentally, socially, economically and energetically sustainable. Biofuels enable employment due to the presence of processing plants in rural areas. They also provide socioeconomic benefits, promote economic dynamism and have the potential to positively affect other related industries (Gilio & Moraes 2016; Moraes et al. 2016).

Sorghum x Sudan grass hybrid (*sorghum bicolor x sorghum sudanense stapf*.) is a plant species with C4 metabolism, that is annual, with wide adaptability, sugar-rich stalk and high biomass yield, and has potential as an energy plant. It can also be grown in marginal areas due to low water and fertilizer requirements. In addition to its potential as an energy plant, it can also be used as a forage plant.

Energy crops, one of the sources of biofuels, are produced in agricultural production systems. It is necessary to optimize the use of agricultural inputs in order to reduce environmental impacts and save energy in agricultural production systems. To reduce the environmental impacts of agricultural production, it is necessary to determine the environmental impacts. The agricultural life cycle assessment (LCA) method is used to determine these environmental impacts. Agricultural LCA is a method for determining the environmental impacts of inputs in the agricultural production system from the cultivation of soil to the harvesting of the product on the basis of environmental impact categories. Agricultural LCA is the application of the LCA method only from cradle to gate, not from cradle to grave, in order to determine the environmental impacts of agricultural activities. Since the agricultural product obtained is raw material for another product, LCA is carried out until the product is obtained (Eren & Öztürk 2021).

There are some agricultural life cycle assessment studies conducted to determine the environmental impacts of agricultural products during production. For example, research was carried out about energy crops (Christoforou et al. 2016), maize (Boone et al. 2016; Zhang et al. 2018; Frank et al. 2020), sunflower (Vatsanidou et al. 2020), sweet sorghum (Eren & Öztürk 2021), agricultural production (Wowra et al. 2021; Fan et al. 2022), potato (Economou et al. 2023) and barley (Stylianou et al. 2023).

Although there are many studies about LCA in the literature, studies about LCA of agricultural production in Türkiye are limited. Therefore, in this study, agricultural LCA was conducted to determine the environmental impacts of sorghum x Sudan grass hybrid biomass production.

2. Material and Methods

2.1. Materials

The research was carried out in the field at Bingöl University Agricultural Application and Research Center (38°48'46,77" N - 40°32'11,40" E) in 2020 (Figure 1). The elevation of the research area is 1100 meters above sea level.

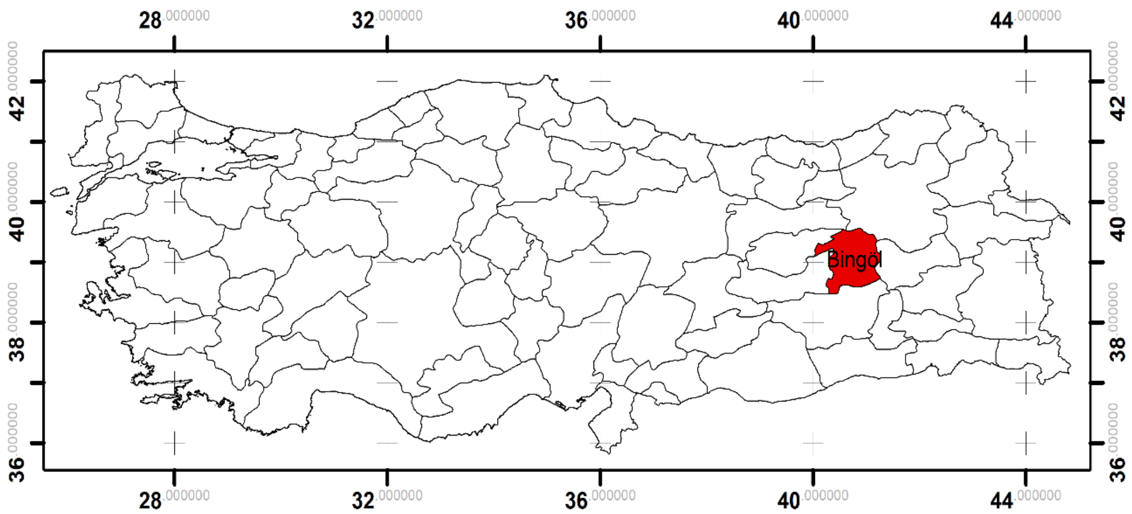


Figure 1- Location of the experimental site in Türkiye

In the experimental area, which has a semi-humid climate, the total precipitation amount in the vegetation periods (June, July, August and September) was 17.5 mm and the average temperature was 24.9 °C. During the cultivation of the sorghum plant, there is temperature demand of 20-35 °C and a water requirement of 500-600 mm (Guiying et al. 2003). During the research, the seasonal temperature in the experimental area met the temperature needed by the plant. However, since there was not enough precipitation, irrigation was needed during the vegetation period. According to the results of soil analysis carried out in the experimental area, the soil was salt-free, limeless, low in organic matter and weak in terms of N, P, K content.

2.2. Cultural practices of sorghum x Sudan grass hybrid production

Cultural practices and maintenance processes in the production of sorghum x Sudan grass hybrid were carried out as follows.

- Tillage: Deep plowing was done, followed by tillage with a cultivator.

- Sowing: In the second week of June, sowing was done at a depth of 3-4 cm with 45 cm row spacing and 5 m row length. Sowing was done so 4 kg of seeds fell per decare.

- Maintenance: 10 kg of 15-15-15 compound fertilizer per decare as base fertilizer and 22 kg of urea 46% N per decare as top fertilizer was given with planting. Hoeing was done when the plant reached 30-40 cm in height. The plant was watered by the drip irrigation method. Insecticide with 50 g/L lambda-cyhalothrin active ingredient was used once for aphids.

- Harvest: After the second week of September, the plant was harvested at full maturity with a scythe motor.

2.3. Sorghum x Sudan grass hybrid ethanol yield

Theoretical ethanol yield was calculated using the formula; [(total sugar / 5.68) x 3.78)] x 0.80 (Smith et al. 1987; Bunphan et al. 2015).

2.4. Determination of environmental impacts

The agricultural LCA method was used to determine the environmental impacts during crop production. Agricultural LCA was carried out in 4 stages of goal and scope definition, inventory analysis, environmental impact assessment and interpretation.

2.5. Goal and scope definition

According to the agricultural LCA, the system boundary in Figure 2 was defined in order to determine the environmental impacts due to cultural practices and maintenance processes during the production of sorghum x Sudan grass hybrid biomass.

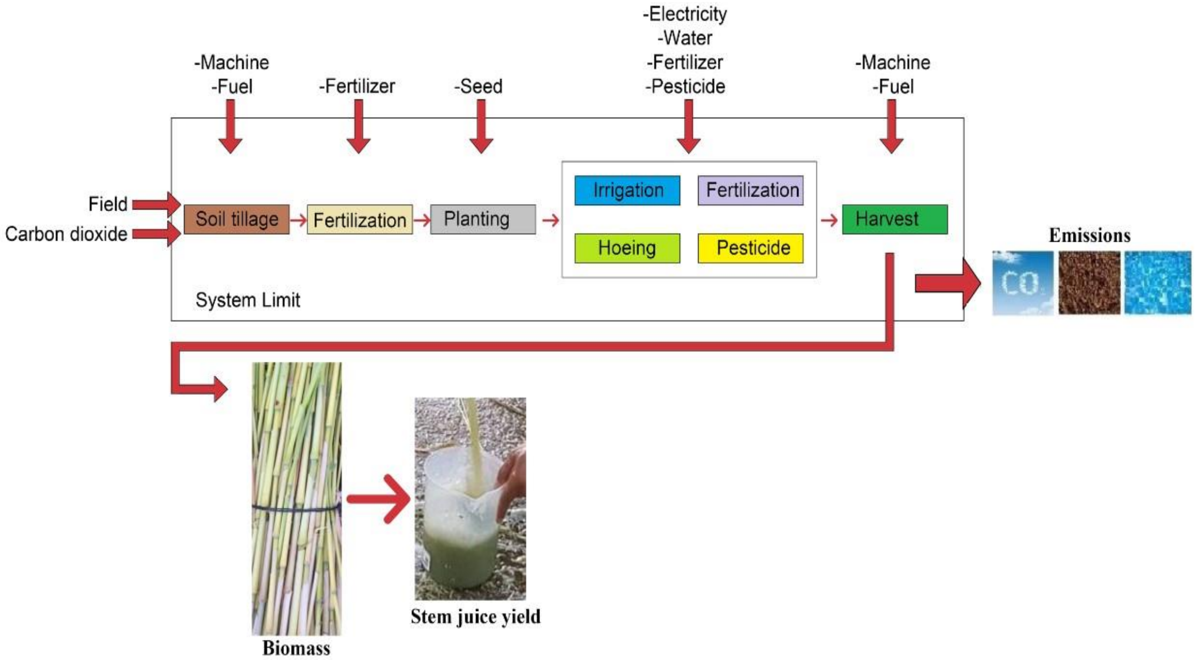


Figure 2- System boundaries of the production system

According to the defined system boundary, agricultural machinery, fuel, fertilizer, seeds, pesticides and water are considered inputs. The biomass of the harvested product and emissions (to air, soil and water) are accepted as outputs (Figure. 2).

A functional unit is a unit that provides reference by normalizing all data and impact categories in the assessment. Different functional units can be selected in agricultural life cycle assessments. In this study, sorghum x Sudan grass hybrid cultivation area (1 ha) and dry biomass amount (1 $kg_{biomass}$) were accepted as functional units.

2.6. Inventory analysis

The following assumptions were made in order to carry out the life cycle inventory analysis of the production system (Table 1).

Table 1- Assumptions

Slope of fields	No slope
Cultivability of fields	Cultivable
Type of agriculture	Irrigated agriculture
Drainage	None
Clay content of soil (%)	54
Humus content of the soil (%)	1.89
Plant potential root depth (cm)	190
Soil erosion (K) factor	Ignored
Fertilization	15-15-15 Compound and 46% N Urea
Machine to prevent ammonia losses	Not used

Then, inventories of the production system were made. The mass balance inventory (agricultural inputs and outputs used during production) values in the production system are given in Table 2 and the inventory data of the machines/tractors used are given in Table 3.

Table 2-Mass balance inventory

Inventories		***Unit***	***Amount Per Hectare (ha^{-1})***
Land Use		ha	1.00
Diesel fuel		l	92.60
Seed		kg	40
	Nitrogen		116.2
Fertilizer	Phosphorus	kg	15
	Potassium		15
Water		m^3	19871.8
Electric		kWh	2504.1
Pesticide		l	0.5
Outputs			
Biomass		kg	49888

Table 3-Agricultural machinery and tractor inventories

Machine	***Mass (kg)***	***Service life (h)***	***Working width (m)***
New Holland TD90D tractor	3700	10000	-
Plow (4 sockets)	800	2000	1.22
Cultivator	350	2000	2.70
Motorized back sprayer	10	2000	-
Motor scythe (4 blades)	7.3	2000	0.23

2.7. Environmental impact assessment

According to the results obtained from the life cycle inventory analysis, the CML-IA Baseline methodology was used in accordance with ISO 14040 standards for the evaluation of the environmental impacts of the biomass production system.
Potential environmental impacts (characterization values) were calculated with SimaPro 8.0.5.13 Analyst software based on the CML-IA Baseline methodology. This CML-IA Baseline methodology includes 11 environmental impact categories (Table 4). After calculating the characterization values, normalization values were calculated by performing normalization with the software. Normalization was done in order to evaluate the impact categories among themselves.

Table 4-Impact categories and characterization units according to the CML-IA Baseline model

Impact Category	***Characterization Unit***
Abiotic depletion	kg Sb_{eq}
Abiotic depletion (fossil fuels)	MJ
Global warming (GWP100a)	kg CO_{2-eq}
Ozone layer depletion (ODP)	kg $CFC11_{eq}$
Human toxicity	kg 1.4-DB_{eq}
Fresh water aquatic ecotoxicity	kg 1.4-DB_{eq}
Marine aquatic ecotoxicity	kg 1.4-DB_{eq}
Terrestrial ecotoxicity	kg 1.4-DB_{eq}
Photochemical oxidation	kg C_2H_{4-eq}
Acidification	kg SO_{2-eq}
Eutrophication	kg PO_{4-eq}

2.8. Interpretation

According to the normalization values, the effects of sorghum x Sudan grass hybrid biomass production system at global, regional and local effects were evaluated and interpreted. To evaluate its global impact, abiotic depletion, abiotic depletion (fossil fuels), global warming (GWP100a) potential, ozone layer depletion (ODP) and marine aquatic ecotoxicity values were considered. To evaluate the regional effects, photochemical oxidation and acidification values were considered. In order to evaluate the local effects, human toxicity, freshwater aquatic ecotoxicity, terrestrial ecotoxicity and eutrophication values were taken into consideration.

3. Results and Discussion

3.1. Theoretical ethanol yield

Biomass yield is one of the most important parameters affecting ethanol yield. The nutrima variety of sorghum x Sudan grass hybrid plant was used as biomass. The amount of ethanol obtained from this variety is 1674.1 l ha^{-1}. In previous studies, some researchers determined that the ethanol yield was between 360-1680 l ha^{-1} (Rao et al. 2013; Rutto et al. 2013; Sawargaonkar et al. 2013; Batog et al. 2020). The findings obtained in the study show that a successful result was obtained in this semi-humid region when compared with the previous studies.

3.2. Potential environmental impacts

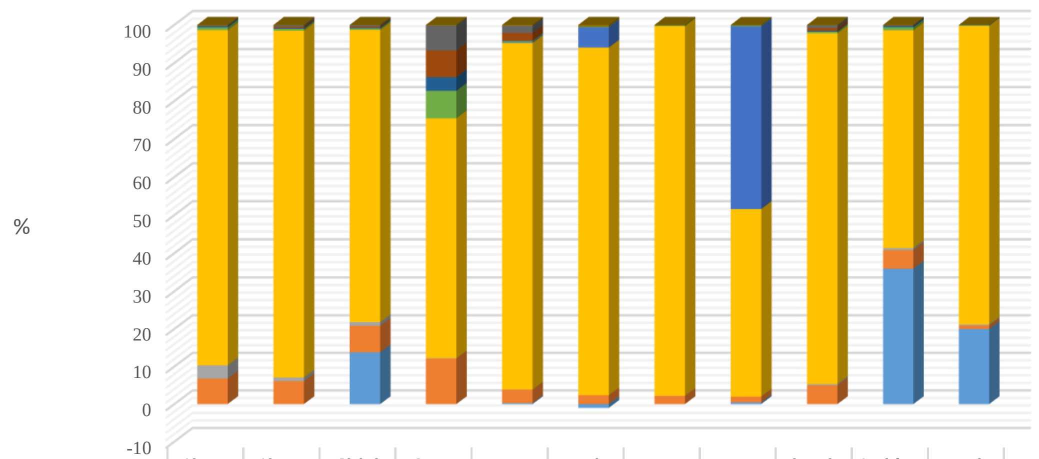
3.2.1. Evaluation of characterization results

As a result of the impact assessment of sorghum x Sudan grass hybrid biomass production, the characterization values in Table 5 and the graph in Figure 3 were obtained. Considering Table 5 and Figure 3 together;

- The abiotic depletion value was calculated as 0.00000074 kg Sb-eq $kg_{biomass}^{-1}$ and the agricultural application causing the most depletion was irrigation (88.31%). In studies carried out on the sorghum plant, this value was obtained as 0.0001188 kg Sb-eq $kg_{biomass}^{-1}$ (Sutter & Jungbluth 2007) and 0.0003163 kg Sb-eq $kg_{biomass}^{-1}$ (Eren &Öztürk 2021).
- Abiotic depletion (fossil fuels) was calculated as 2.223 MJ $kg_{biomass}^{-1}$ and the agricultural application causing the most depletion was irrigation (91.41%).
- Global warming (GWP100a) value was calculated as 0.195 kg CO_2-eq $kg_{biomass}^{-1}$ and the agricultural application causing the most warming was irrigation (76.85%). In previous studies, this value was reported to vary between 0.114-0.517 kg CO_2-eq $kg_{biomass}^{-1}$ (Wang et al. 2014; Eren & Öztürk 2021).
- Ozone layer depletion (ODP) value was calculated as 0.000000012 kg CFC11-eq $kg_{biomass}^{-1}$ and the agricultural application causing the most depletion was irrigation (63.25%). Sutter and Jungbluth (2007) determined this value as 0.00000000211 kg CFC11-eq $kg_{biomass}^{-1}$.
- Human toxicity value was calculated as 0.150 kg 1.4-DB-eq $kg_{biomass}^{-1}$ and the agricultural application causing the most toxicity was irrigation (91.39%). In previous studies, this value was reported to vary between 0.004-0.028 kg 1.4-DB-eq $kg_{biomass}^{-1}$ (Sutter & Jungbluth, 2007; Wang et al. 2014; Eren & Öztürk 2021).
- Fresh water aquatic ecotoxicity value was calculated as 0.084 kg 1.4-DB-eq $kg_{biomass}^{-1}$ and the agricultural application causing the most fresh water ecotoxicity was irrigation (91.69%). This value was calculated as 0.015 kg 1.4-DB-eq $kg_{biomass}^{-1}$ (Sutter & Jungbluth 2007) and 0.023 kg 1.4-DB-eq $kg_{biomass}^{-1}$ (Wang et al. 2014).
- Marine aquatic ecotoxicity value was calculated as 233.792 kg 1.4-DB-eq $kg_{biomass}^{-1}$ and the agricultural application causing the most marine ecotoxicity was irrigation (97.51%).
- Terrestrial ecotoxicity value was calculated as 0.001 kg 1.4-DB-eq $kg_{biomass}^{-1}$ and the agricultural applications causing most terrestrial ecotoxicity were irrigation (49.61%) and insecticides (48.03%). Eren and Öztürk (2021) found this value was 0.00001257 kg 1.4-DB-eq $kg_{biomass}^{-1}$.
- Photochemical oxidation value was calculated as 0.000054 kg C_2H_4-eq $kg_{biomass}^{-1}$ and the agricultural application causing the most photochemical oxidation was irrigation (92.47%). Other researchers reported photochemical oxidation of 0.00000261 kg C_2H_4-eq $kg_{biomass}^{-1}$ (Sutter & Jungbluth 2007) and 0.00000503 kg C_2H_4-eq $kg_{biomass}^{-1}$ (Eren & Öztürk 2021).
- Acidification value was calculated as 0.001 kg SO_2-eq $kg_{biomass}^{-1}$ and the agricultural applications causing the most acidification were irrigation (57.24%) and sorghum x Sudan grass hybrid biomass (35.90%). The reason for this is the increase in organic acids in soil which are produced as a result of the biological activities of the plant related to the decomposition of plant tissues by small soil creatures.
- Eutrophication value was calculated as 0.002 kg PO_4-eq $kg_{biomass}^{-1}$ and the agricultural applications causing the most eutrophication were irrigation (78.57%) and sorghum x Sudan grass hybrid biomass (19.99%). The reason for this is that the plant could not retain the nitrate from fertilization during cultivation and the nitrate that was not retained infiltrated into the soil.

Table 5- Life cycle impact indicators of sorghum x Sudan grass hybrid biomass production (per functional unit of product produced)

Impact Category	*Unit*	*Unit* $kg_{biomass}^{-1}$	*Unit* ha^{-1}
Abiotic depletion	kg Sb-eq	0.00000074	0.03691712
Abiotic depletion (fossil fuels)	MJ	2.223	110901.02
Global warming (GWP100a)	kg CO_2-eq	0.195	9728.16
Ozone layer depletion (ODP)	kg CFC11-eq	0.000000012	0.000598656
Human toxicity	kg 1.4-DB-eq	0.150	7483.20
Fresh water aquatic ecotoxicity	kg 1.4-DB-eq	0.084	4190.59
Marine aquatic ecotoxicity	kg 1.4-DB-eq	233.792	11663415.30
Terrestrial ecotoxicity	kg 1.4-DB-eq	0.001	49.88
Photochemical oxidation	kg C_2H_4-eq	0.000054	2.693952
Acidification	kg SO_2-eq	0.001	49.88
Eutrophication	kg PO_4-eq	0.002	99.77



	Abiotic depletion	Abiotic depletion (fossil fuels)	Global warming (GWP100a)	Ozone layer depletion (ODP)	Human toxicity	Fresh water aquatic ecotoxicity	Marine aquatic ecotoxicity	Terrestrial ecotoxicity	Photochemical oxidation	Acidification	Eutrophication
Electric	0.13	0.09	0.12	0.14	0.22	0.45	0.13	0.12	0.11	0.07	0.02
Pesticide application	0.09	0.35	0.30	6.56	1.91	0.01	0.01	0.01	0.71	0.07	0.01
Harvest	0.10	0.38	0.32	7.03	2.05	0.01	0.01	0.01	0.77	0.13	0.02
Tillage (Cultivatör)	0.34	0.23	0.19	3.59	0.08	0.05	0.04	0.07	0.21	0.39	0.07
Tillage (Plow)	0.74	0.47	0.41	7.23	0.26	0.14	0.11	0.17	0.43	0.77	0.15
Pesticide	0.00	0.00	0.00	0.00	0.24	5.32	0.00	48.03	0.00	0.00	0.00
Irrigation	88.31	91.41	76.85	63.25	91.39	91.69	97.51	49.61	92.47	57.24	78.57
EC Fertilizer NPK (15-15-15)	3.49	0.96	0.95	0.09	0.01	0.00	0.01	0.01	0.31	0.54	0.24
EC Fertilizer (%46 N)	6.81	6.10	7.09	12.09	3.61	2.34	2.17	1.53	4.99	4.89	0.92
Sorghum & sudangrass hybrid biomass	0.00	0.00	13.77	0.00	0.24	-1.00	0.00	0.44	0.00	35.90	19.99

Figure 3- % comparison of characterization values

3.2.2. Evaluation of normalization results

Normalization was done in order to compare the environmental effects among themselves. The normalization results and the impact categories were compared among themselves (Figure 4) and their distribution in % was evaluated (Table 6).

Table 6- % distribution of the comparison of impact categories among themselves

Impact Category	*%*
Abiotic depletion	0.35
Abiotic depletion (fossil fuels)	2.80
Global warming (GWP100a)	1.53
Ozone layer depletion (ODP)	0.01
Human toxicity	0.77
Fresh water aquatic ecotoxicity	6.42
Marine aquatic ecotoxicity	79.21
Terrestrial ecotoxicity	0.80
Photochemical oxidation	0.25
Acidification	2.02
Eutrophication	5.87
Total	*100.00*

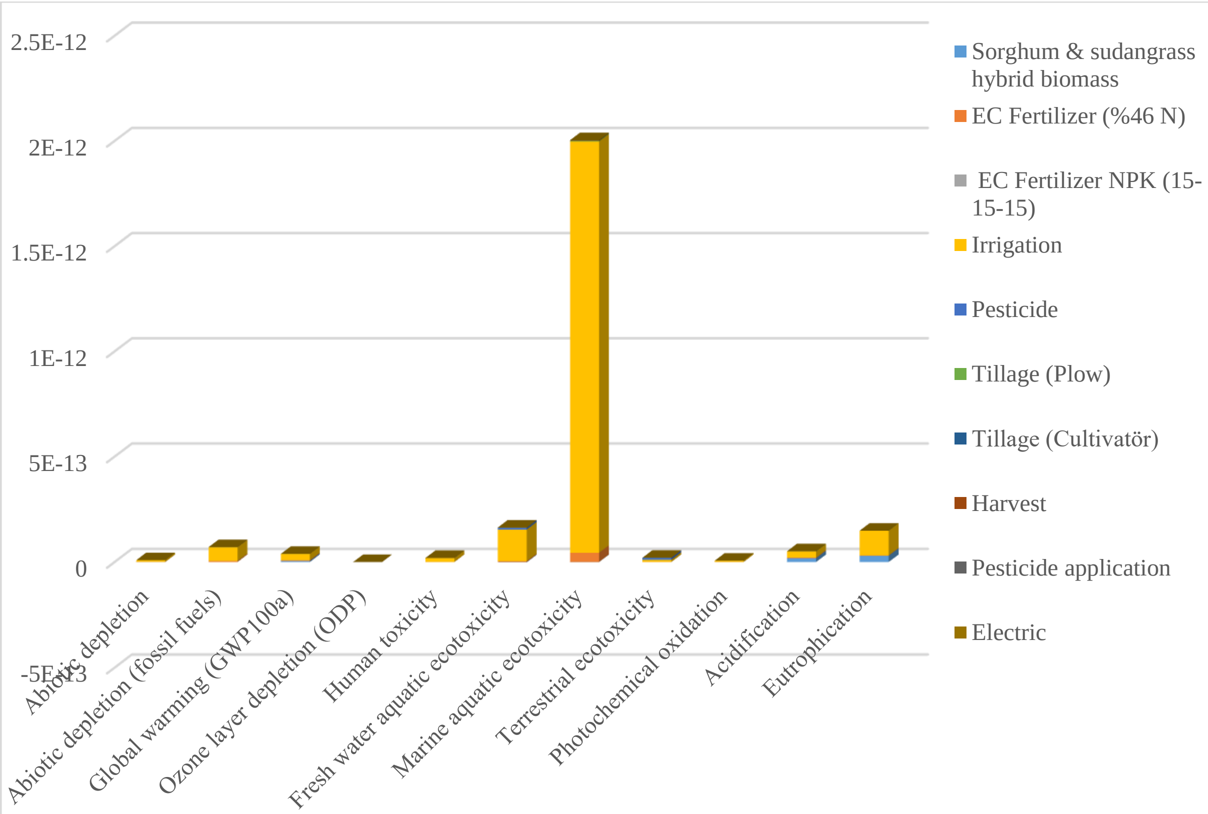


Figure 4- Comparison of normalization values on the basis of impact categories

When Table 6 and Figure 4 are examined together, the production of sorghum x Sudan grass hybrid biomass caused the most marine aquatic ecotoxicity (79.21%). Marine aquatic ecotoxicity is followed by the effects of fresh water aquatic ecotoxicity (6.42%) and eutrophication (5.87%), respectively. The effects of abiotic depletion, global warming (GWP100a), ozone layer depletion, human toxicity, terrestrial ecotoxicity and photochemical oxidation comprised less than 2% in the production system, and can be ignored.

3.3. Interpretation

3.3.1. Global influences

When the impact categories that cause global influence is evaluated among themselves (Figure 5), marine aquatic ecotoxicity (94.42%) caused the most global influence. Irrigation applications (97.51%) in the agricultural phase have the greatest impact on marine aquatic ecotoxicity (Figure 3). Irrigation studies should be carried out and practices that will minimize the effects of irrigation should be determined. Marine aquatic ecotoxicity value was followed by the effect of abiotic depletion (fossil fuels) (3.33%) (Figure 5). Irrigation applications in the agricultural phase (91.41%) were effective in increasing the effect of abiotic depletion (fossil fuels).

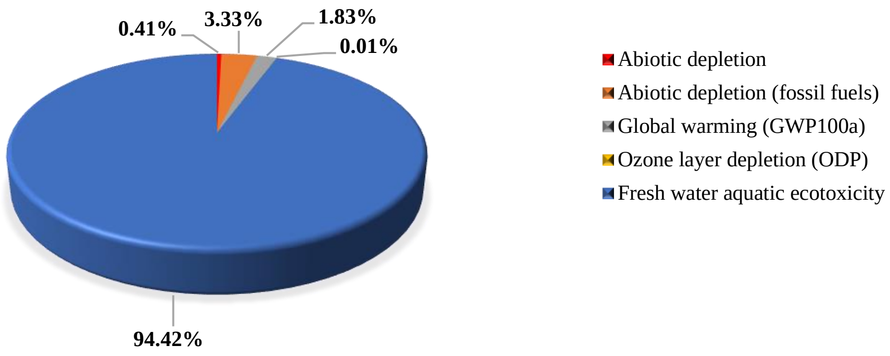


Figure 5- Distribution of impact categories that cause global influences

Due to the increasing effect of abiotic depletion (fossil fuels), it is estimated that natural resources, especially fossil fuels, will be depleted in the near future. Another factor that causes a global effect is the global warming potential (1.83%) (Figure 5). It is predicted that global warming will cause a melting of ice at the poles and a change in seasons, and thus climate change, in the next 100 years. The values for abiotic depletion and ozone layer depletion affect the global influence at very low rates.

3.3.2. Regional influences

When the impact categories causing regional influence were evaluated among themselves (Figure 6), the acidification effect (88.93%) caused the most regional influence. Irrigation applications in the agricultural phase (57.24%) caused an increase in the acidification effect (Figure 3). In addition, the effect of photochemical oxidation was determined as 11.07% on a regional scale.

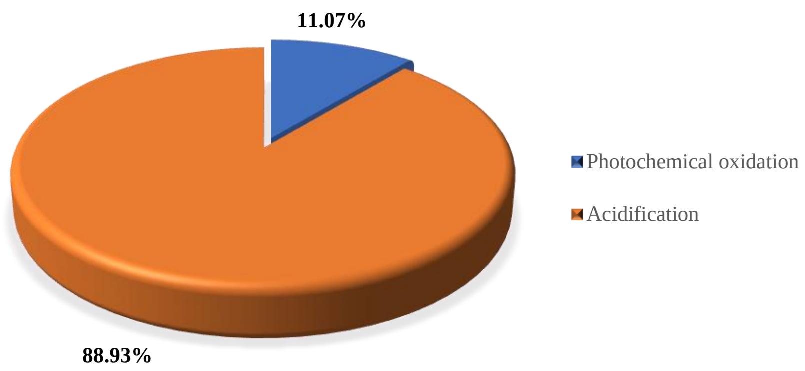


Figure 6- Distribution of impact categories that cause regional influences

The application that caused the most photochemical oxidation was irrigation (92.47%) (Figure 3). It is assumed that over-irrigation causes acidification of the soil. For this reason, acidification and corrosion may occur in soils or wetlands of the region. This may result in the restriction of other products that can be grown and the decrease in the yield of the products that can be grown.

3.3.3. Local influences

When Figure 7 is examined, the effect of fresh water aquatic ecotoxicity was 46.34%. This effect also negatively affects the environment locally. Fresh water aquatic ecotoxicity was followed by the eutrophication effect (42.38%).

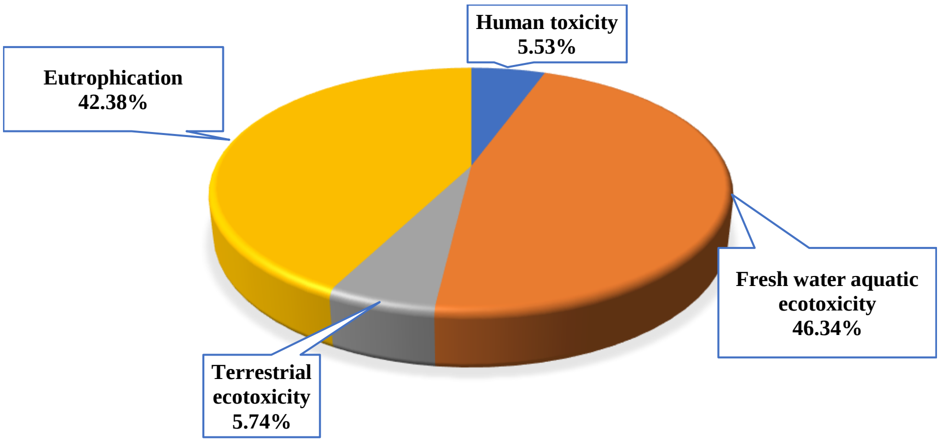


Figure 7- Distribution of impact categories that cause local influences

Irrigation practices in the agricultural phase caused an increase in fresh water aquatic ecotoxicity (91.69%) and eutrophication (78.57%) (Figure 3). Where biomass is grown, there may be a decrease in fresh water species and biodiversity.

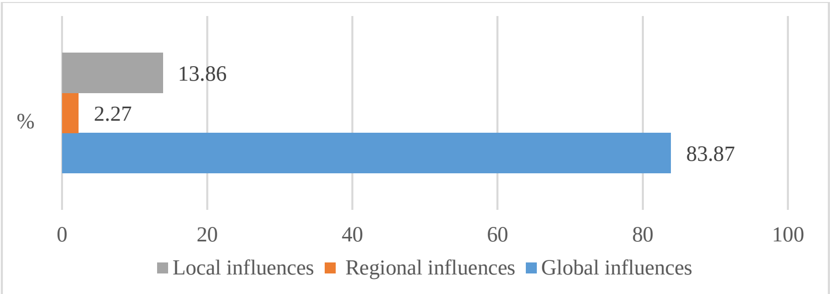


Figure 8- Comparison of impact categories with each other

When all the effects are evaluated together (Figure 8), the production of sorghum x Sudan grass hybrid biomass caused the largest impact on a global scale (83.87%). The global influence was followed by the local influence (13.86%) and the regional influence (2.27%).

4. Conclusions

According to the % distribution for normalized values of agricultural LCA of cultivating sorghum x Sudan grass hybrid plant for biomass production, the highest environmental impact with a rate of 79.21% was marine aquatic ecotoxicity. According to the agricultural life cycle assessment, production has a global influence with a rate of 83.87%. In addition, the global warming potential was calculated as 0.195 kg CO_2-eq $kg_{biomass}^{-1}$ (9728.16 kg CO_2-eq ha^{-1}).

Irrigation applications in the agricultural phase are the environmental pollutants with highest impact. Excessive water consumption causes environmental pollution. In addition, water resources in the world are decreasing due to drought resulting from climate change. Since excessive use of water in agriculture affects the environment negatively and consumes water resources, research should be increased to reduce water use by developing irrigation technologies. Agricultural life cycle assessments associated with many products should be made and the environmental impacts of the growing process of the products should be determined. Studies should be increased about the establishment of inventory databases for agricultural life cycle assessment for agricultural products around the world.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have influenced the work reported in this paper. This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

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