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Research Article

Minimizing Greenhouse Gas Emissions from a Horizontal Subsurface Flow Constructed Wetland

Bir Yatay Yüzey Altı Akışlı Yapay Sulak Alanın Sera Gazı Emisyonlarının Minimizasyonu

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Abstract

In this study, the level of carbon dioxide, methane and nitrous oxide emissions from a horizontal subsurface flow constructed wetland were monitored and greenhouse gas emissions were estimated by using a newly developed model. The effects of three different plant species on greenhouse gas emissions were investigated. *Cyperus esculentus* (Zone I), *Typha latifolia* (Zone II) and *Phragmites australis* (Zone III) were selected as the experimental species. Greenhouse gas emissions were sampled twelve times totally by using the closed chamber method between January and December. The highest level of emission was measured for nitrous oxide emission, released from Zone I in August (10,8371 kg CO_2e/d). The lowest level of emission was measured for carbon dioxide emission (0,0156 kg CO_2e/d) at Zone III in January. The results revealed that *Cyperus esculentus* has the highest greenhouse gas emission and the highest Global Warming Potential. All greenhouse gas emissions were influenced from different plant species. *Phragmites australis* could be used for minimizing the level of greenhouse gas emissions as it has the lowest level of greenhouse gas emission and Global Warming Potential. Finally, the possible level of greenhouse gas emission is estimated by using Monte Carlo simulation if the wetland is vegetated with only *Phragmites australis*. Approximately 33% of greenhouse gas emissions could be reduced if the wetland is vegetated only *with Phragmites australis*.

Keywords: *Horizontal subsurface flow constructed wetland, greenhouse gas emission, the effects of plants*

Öz

Bu çalışmada, bir yatay yüzey altı akışlı yapay sulak alanda oluşan karbon dioksit , metan ve nitröz oksit emisyonları izlenmiş ve yeni geliştirilen bir model kullanılarak sera gazı emisyonları tahmin edilmiştir. Üç farklı bitki türünün sera gazı (SG) emisyonları üzerindeki etkisi araştırılmıştır. Deneysel türler olarak *Cyperus esculentus* (Bölge I), *Typha latifolia* (Bölge II) ve *Phragmites australis* (Bölge III) seçilmiştir. Gaz örneklemesi, Ocak-Aralık ayları arasında kapalı çember yöntemi ile toplamda on iki kez gerçekleştirilmiştir. En yüksek emisyon, Ağustos ayında Bölge I'den salınan

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N_2O emisyonudur (10,8371 kg CO_2e/d). En düşük emisyon Ocak ayında III. Bölge'deki CO_2 emisyonudur (0,0156 kg CO_2e /d). Sonuçlar, Cyperus esculentus'un en yüksek sera gazı emisyonuna ve en yüksek küresel ısınma postansiyeline sahip olduğunu ortaya koymaktadır. Phragmites australis, en düşük sera gazı emisyonuna ve en düşük küresel ısınma potansiyeline sahip bitki olarak kullanılabilir. Tüm sera gazı emisyonları farklı bitki türlerinden etkilenmiştir. Phragmites australis düşük sera gazı emisyonu yayması ve küresel ısınma potansiyeli nedeniyle sera gazı emisyonunu azaltmak için kullanılabilir. Son olarak, sulak alan sadece Phragmites australis ile bitkilendirilmesi durumu için, olası sera gazı emisyonu Monte Carlo simülasyonu kullanılarak tahmin edilmiştir. Sulak alan sadece Phragmites australisle bitkilendirilmiş olsaydı, sera gazı emisyonlarında yaklaşık % 33 azalma elde edilebileceği görülmüştür.

Anahtar kelimeler: *Yatay yüzey altı akışlı yapay sulak alan, sera gazı emisyonu, bitkilerin etkisi*

Introduction

It is an economical method to use aquatic plants for wastewater treatment, especially where the land is abundant and therefore cheap. In addition, eutrophication could be prevented by installing such systems in the lakes and wetlands (Metcalf & Eddy, 2014). It is possible to collect aquatic plants, used in wastewater treatment, in three groups as submerged aquatic plants, rooted water plants and floating aquatic plants. Especially, wetlands which are regarded as the rooted water plants systems are commonly used for wastewater treatment. There are several constructed wetlands applications in Turkey as wastewater treatment systems.

Natural treatment systems such as constructed wetland could be more applicable, feasible, and also they have many advantages due to low cost and effective pollutant removal mechanisms (Metcalf & Eddy, 2014). Constructed wetlands are regarded as a low cost and sustainable system to treat different types of wastewater. In addition to municipal wastewater, agricultural, industrial and leachate could be treated by constructed wetlands. Vegetation in wetlands disposes pollutants from wastewater by plant uptake and harvesting. Vegetation in wetlands could be influenced by temperature and influent wastewater quality (Martinez-Guerrae et al., 2015). The treatment of wastewater in constructed wetlands is mainly based on microbial degradation of pollution in the wastewater [organic matter is decomposed to gases mostly carbon dioxide (CO_2) and methane (CH_4), nitrogen is transformed to gaseous compounds nitrous oxide (N_2O) and these gases are emitted to the atmosphere.].

The advantage of constructed wetlands as compared to conventional treatment systems is low operation and maintenance costs. In addition to nutrient removal, greenhouse gas emissions are emitted from constructed wetlands. Despite many advantages, constructed wetland releases significant amount of greenhouse gases which are formed under anoxic condition of flooded area. The greenhouse gases from constructed wetlands also have a seasonal and temporal diversity resulting from the microbial processes (Chiemchaisri et al., 2009).

Greenhouse gas emissions from wastewater treatment process have been considered as an important environmental challenge by the authorities in recent years (Kyung et al., 2015; Gülşen & Yapıcıoğlu, 2019). Wastewater treatment plants are released three main greenhouse gases which are CO_2, CH_4 and nitrous oxide N_2O due to treatment process, sludge handling and stabilization process, chemical use, energy consumption and maintenance and repair activities (Rodriguez-Caballero et al., 2014; Kyung et al., 2015). Greenhouse gas emissions can be categorized as on-site emissions and off-site emissions (Paravicini et al., 2016). On-site greenhouse gas emissions are those: 1) released in the sewage collection system, 2) resulted from wastewater treatment processes and 3) where the effluent is discharged. Off-site greenhouse gas emissions are occurred by the electricity consumption, air consumption, transportation, chemical use and disposal and reuse processes (Paravicini et al., 2016).

Constructed wetlands are regarded as one of the wastewater treatment units which significantly emit greenhouse gas emissions (Mander et al., 2014). Especially, CO_2, CH_4 and N_2O emissions are emitted from constructed wetlands (Mander et al., 2014) due to treatment process. There are many factors on greenhouse gas emission reduction in constructed wetlands. The impact of plant species diversity on greenhouse gas emissions has gained much significance (Han et al., 2019). Plants species can vary greatly in the vegetation, consumption, and transport of CO_2, CH_4 and N_2O (Han et al., 2019). These variations are majorly defined by anatomical characteristics of species (Han et al., 2019). Plant species diversity could reduce CO_2, CH_4 and N_2O emissions by enhancing nitrogen uptake and carbon capture. CO_2 could be minimized due to photosynthesis. However, several studies have demonstrated that plant species diversity increases the amount of CH_4 and N_2O emissions due to plant species with aerenchyma (Zhang et al., 2012; Chang et al., 2014), while some studies have reported that CH_4 and N_2O emissions have not been affected by species diversity (Abalos et al., 2014; Zhao et al., 2016).

In this study, it is aimed to reveal the effects of different plant species on greenhouse gas emissions from a horizontal subsurface flow constructed wetland in Turkey. CO_2, CH_4 and N_2O emissions from a horizontal subsurface flow constructed wetland are observed twelve times in total using closed chamber method. Also, global warming potential (GWP) of the plant species are determined using Life Cycle

Assessment (LCA) approach considering all GHG emissions. A new developed model based on Intergovernmental Panel on Climate Change (IPCC) method is used to estimate the GHG emissions. The novelty of this study is that a new GHG emission estimation tool is developed for the constructed wetlands. The constructed wetland is divided into 3 zones. *Cyperus esculentus* (Zone I), *Typha latifolia* (Zone II) and *Phragmites australis* (Zone III) are planted as the vegetation species. The originality of this work is that the effects of *Cyperus esculentus, Typha latifolia and Phragmites australis* on GHG emissions are determined in terms of CO_2, CH_4 and N_2O emission for a horizontal subsurface flow constructed wetland. Apart from the studies in the literature, not only CH_4 and N_2O emissions but also CO_2 emission is considered in this paper for these three species using a new developed GHG estimation tool. The other originality of this study, the GHG originated from *Cyperus esculentus* and *other plants* were estimated for a full-scale horizontal subsurface flow constructed wetland. Also, one of the originalities of this work is that LCA methodology is carried out for the determination of global warming potentials related to plant species based on in situ GHG monitoring results. LCA is a method to categorize the effects corresponded with all the phases of a product, service, or process from cradle to grave. LCA is implemented for a product of a process in general; this methodology could be also applied to the environmental impact assessment of a wastewater treatment process.

In the final stage of the study, possible GHG emission was determined using Monte Carlo simulation if Zones (I-II) were vegetated with the plant species which released the lowest GHG emission. The other originality of this work was that Monte Carlo simulation was applied to simulate the possible GHG emission if all zones were vegetated with the plant species which has the lowest global warming potential.

Method

Description of the Study Area

The constructed wetland was built on nearly 0,2-hectare land in the southeastern of Turkey and by the Tigris River. It is a type of horizontal subsurface flow constructed wetland. Clay material was used to seal wetland chamber. In the artificial wetland reservoirs, sieved-washed stream pebbles and circulating stream material were used as bed fill material. The municipal wastewater originated from a village near the Tigris River was treated in this constructed wetland. The influent wastewater characterization was given in Table 1. Wastewater analyses were performed according to the standard methods (American Public Health Association [APHA], 1998).

Table 1

Influent Characterization of the Municipal Wastewater

Parameter	Value
COD (mg/L)	203,2 – 1401,2
TSS (mg/L)	40 – 200
BOD (mg/L)	80,8 – 800,3
TKN (mg/L)	66-75
pH	6,5-7,5
Flow rate (m^3/d)	400-450

**COD: Chemical Oxygen Demand;*TSS: Total Suspended Soils; *BOD: Biochemical Oxygen Demand; *TKN: Total Kjeldahl Nitrogen*

Figure 1 demonstrated the wastewater treatment flow scheme in the constructed wetland. Influent is fed and flows through the porous media under the surface of the bed planted with emergent vegetation to the outlet, where it is collected before leaving via a water level in horizontal subsurface flow constructed wetland. There are 3 vertical flow filtration beds on the wetland. Equalization tank is used as preliminary treatment before the wetland. The constructed wetland has 60 cm of water depth, about 42 m^2 of cross-sectional area, 70 m of length and 40,6 m of width. The surface area of the constructed wetland is approximately 2.842 m^2. The volume of the constructed wetland is about 1.705 m^3.

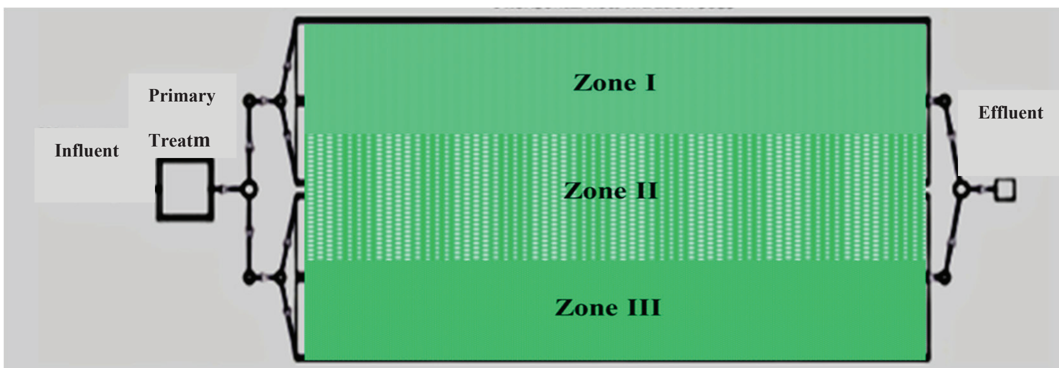
There are 3 zones at the wetland. The zones contain three different vegetation. Planting area is with a depth of 20 cm in bed. Harvesting beds are prepared to be at least 14 m^2 of cross-sectional area.

Plant Species at Horizontal Subsurface Flow Constructed Wetland

Three common plants, *Cyperus esculentus*, *Typha latifolia* and *Phragmites australis* were selected as the experimental species in this study. The reason of selecting these plants was that they are obtained easily in Turkey and can grow well in this system. These species are categorized under the group of rooted and float plants. These plants are also resistant to sunny and arid areas. They can survive at fresh water.

Figure 1

Wastewater Treatment Process Flow Diagram of Constructed Wetland

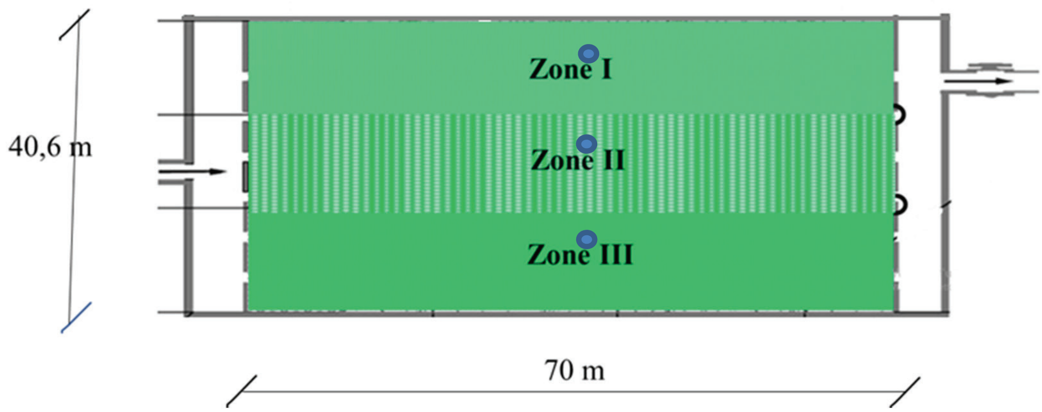


Cyperus esculentus, *Typha latifolia*, and *Phragmites australis* were from Adana, Sakarya and Hatay respectively. These plants were obtained and picked from the nature by the researchers. There is no need for the permission of picking the plants. The wetland was divided into three main regions. Zone I majorly contains *Cyperus esculentus*. *Typha latifolia* is the dominant species at Zone II. Zone III contains mostly *Phragmites australis*. Figure 2 demonstrates the plant zones that contain the plan of the constructed wetland. GHG emission sampling points are the Zone I, Zone II, and Zone III. The surface areas of the zones are equal whose values are about 947.3 m^2. *Cyperus esculentus*, *Typha latifolia* and *Phragmites australis* are under classification of the submerged plant species. All of them are young plants.

These three plant species were planted in spring according to the characteristics of the species before the measurement. All plant species were the same age and one years old. These plant species were harvested in winter. Some plant analyses were applied to determine the dominant plant in the wastewater.

Figure 2

Plant Zones and GHG Monitoring Points of Constructed Wetland in The Plan



Note. GHG Emission Monitoring Point.

Closed Chamber Method and Gas Sampling

Several emission monitoring methods have been developed for WWTPs such as open chamber method, closed chamber method and static chamber method (Masuda et al., 2015). The closed chamber gas measurement method is one of the methods of measurement and determination of greenhouse gases worldwide for wastewater treatment. The closed chamber method was applied to measure the emissions from the constructed wetland. The closed chamber had a cross-sectional area of 0,118 m^2 and the volume of 25 L. It consisted of a portable top and a round Styrofoam base. The gas was pumped into this chamber and collected for 30 min. The gas analyzer was placed in the pump. Drager Polytron fixed 605 multi-gas analyzer was used to determine the GHG concentrations. The optimum gas retention time was assigned as 30 minutes due to observing no increase in the gas concentration in the end of 30 minutes. The gas flux (F) can be considered as the volume of the closed chamber. F was approximately 1,2 m^3/d (it has been figured out using the volume of the closed chamber and the gas retention time). The same closed chamber was used for all zones and 3 plant species. The same gas monitoring method was applied for all zones and plant species. All zones were monitored the same day and respectively. The monitoring points of 3 zones were the top of the zones. The GHG monitoring points were shown in Figure 2. All gas samplings were carried out from the same point.

Gas sampling was performed using the closed emission chamber for each zone. Each zone has been monitored twelve times totally (Zone I-III) between January and December, from the same points. CO_2, CH_4 and N_2O gas concentrations were determined using Drager Polytron fixed 605 multi-gas analyzer.

Estimation of Greenhouse Gas Emission

GHG emissions were determined from F (m^3/d) and gas concentrations in the closed chamber. GHG concentration (mg/m^3) (C_{GHG}) was determined using Drager Polytron fixed multi-gas analyzer. GHG concentration (mg/m^3) was multiplied with F (1,2 m^3/d). GHG emissions were converted to CO_2-equivalent emissions by multiplying GWP of each gas (Intergovernmental Panel on Climate Change [IPCC], 2014). GWP of CO_2, CH_4 and N_2O are 1, 28 and 265 respectively. Equation 1 shows the calculation of GHG emission.

$$GHG\ (kgCO_2e/d) = [(F \times C_{GHG}) / 1000000)] \times GWP \quad (1)$$

Determination of Global Warming Potential

LCA enables for a better assessment of wastewater treatment technologies in several different approaches. Due to its holistic approach, LCA is regarded as an increasingly crucial decision-making tool in environmental issues (Büyükkamacı & Gökçe, 2017). In this study, the LCA was carried out using GaBi 6.1 Software Thinkstep, Germany. The CML 2001 impact assessment method was used to determine the GWP of the three plant species. The required data for the software was ensured from the GHG monitoring results of the closed chamber and the Eco-invent database, which is integrated into the GaBi 6.1 software. GaBi software run according to a designed flow diagram and defined inputs and outputs. The system boundary defines which inputs and outputs contain. Electricity consumption and chemical use were ignored in this study due to belonging a natural treatment system. The inputs of this study are mainly treated wastewater characterization and wastewater treatment efficiency. The variables were influent and effluent BOD, COD and TKN concentrations. The outputs were N_2O, CH_4 and CO_2 emissions. The main function of this study is to determine the global warming potential of the *Cyperus esculentus, Typha latifolia* and *Phragmites australis* at a horizontal subsurface flow constructed wetland.

Simulation of the GHG Emissions

In the final stage of the study, possible GHG emission was simulated using Monte Carlo simulation if Zones (I, II) were vegetated with the plant species which released the lowest GHG emission. Monte Carlo simulation was used to simulate all GHG emissions related to Zones (I, II) if all zones were vegetated with the plant species which has the lowest global warming potential.

Monte Carlo simulation has been developed based on computational algorithms that contain repeated random sampling to ensure numerical results. This simulation is applied in physical and mathematical problems in general. Monte Carlo simulation is majorly used in optimization, numerical integration, and generating draws from a probability distribution (Kroese et al., 2014). Monte Carlo Simulation is a mathematical technique that produces random variables to determine the risk or uncertainty of a certain system or in order to optimize the variables. @RISK software was used to perform Monte Carlo simulation. Volumetric Reserves 1-Basic @RISK model, 1000 iterations and 1 simulation were performed for this study. Lognormal distribution was selected as the probability distribution. As uncertain inputs were CO_2, CH_4 and N_2O emissions related to each zone, the outputs were the minimum total GHG emission related to *Phragmites australis*. Therefore, the GHG emissions corresponded to Zone (I-III) were simulated to the lowest GHG emission related to *Phragmites australis.* Equation 2 illustrated the calculation of possible minimum GHG emission.

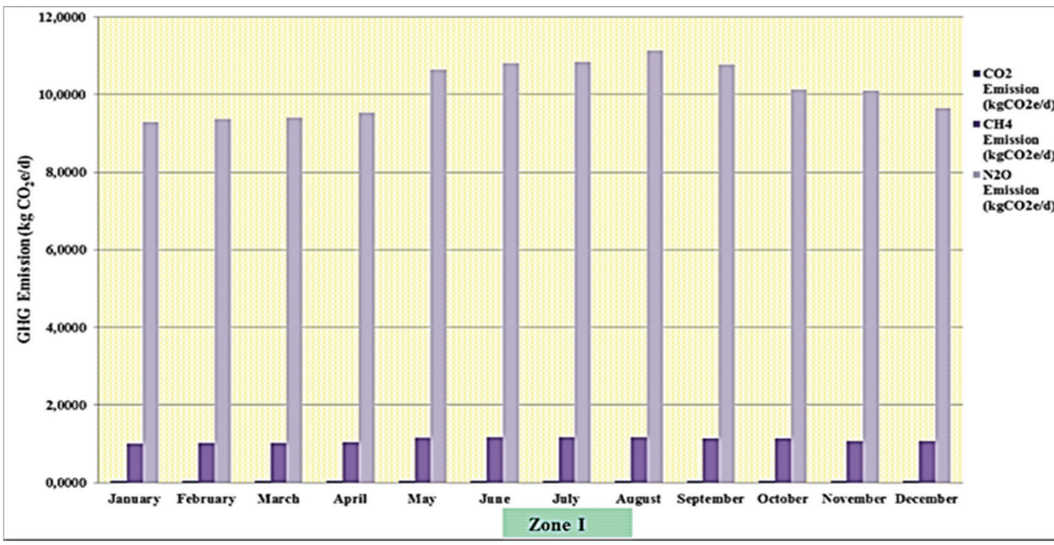
E_{min}= RiskOutput("Lognormal")+RiskLognorm(Z_1;Z_2) (2)
E_{min} = Possible minimum GHG emission
Z_1= Sum of CO_2, CH_4 and N_2O emissions related to Zone (I-III)
Z_2= Total greenhouse gas emission value related to *Phragmites australis*

Results and Discussion

Figure 3 demonstrated the monthly variation of GHG emissions. According to the findings, the highest emission was N_2O emission and the lowest emission was CO_2 emission. The highest GHG emissions were monitored in January in winter and the lowest GHG emissions were monitored in August in summer.

Figure 3

Monthly Variation of GHG Emissions



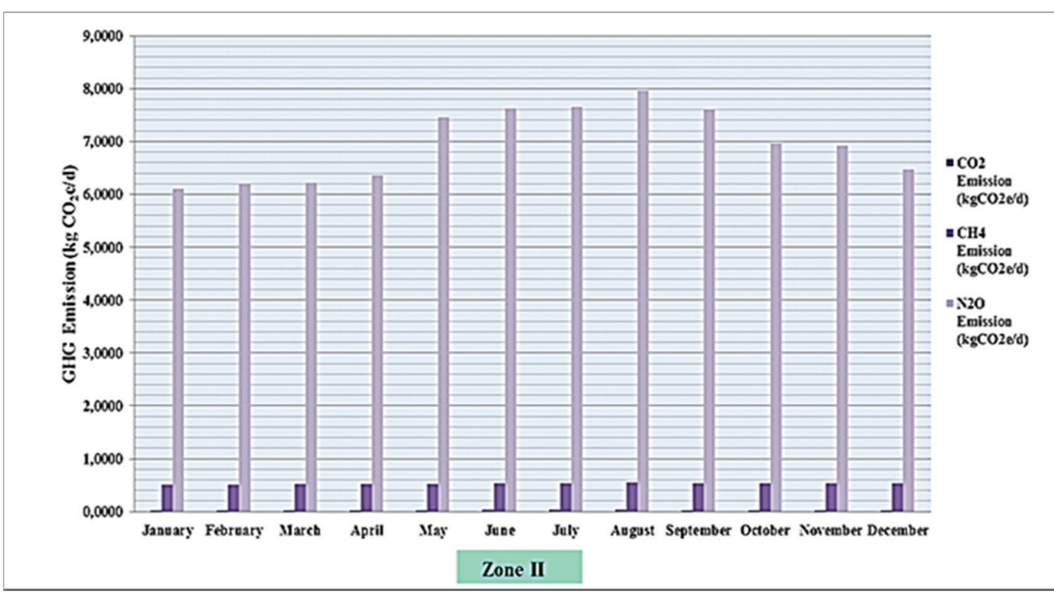


Figure 3

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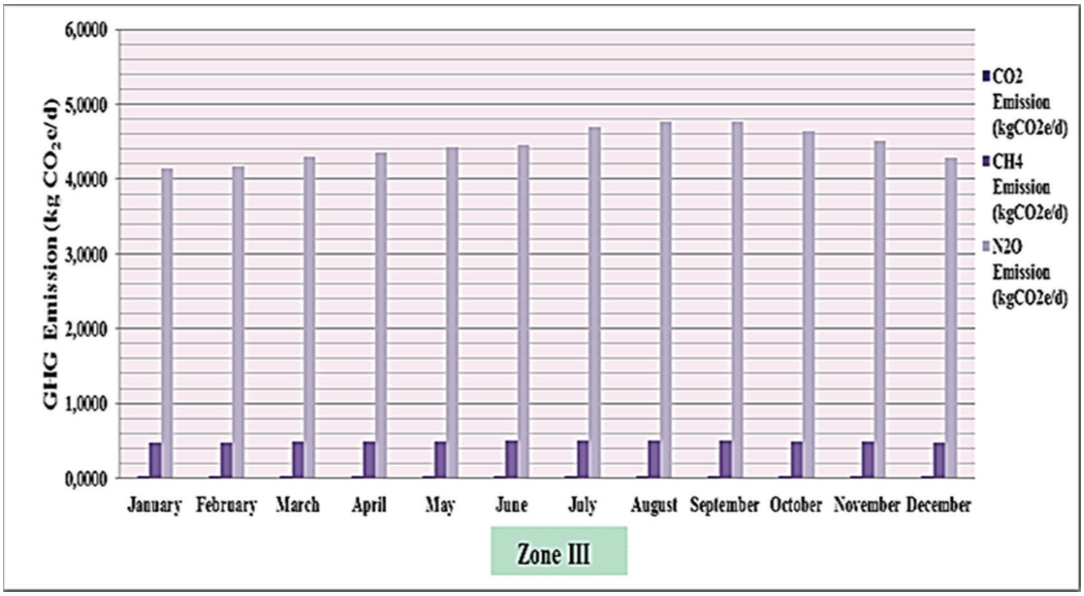


Results of N_2O Emissions Monitoring

Excess nutrients mainly from anthropogenic sources have been demonstrated significantly increase N_2O emissions from wetland soils through denitrification and nitrification processes. The results revealed that N_2O emission was the major GHG emission from each zone of horizontal subsurface flow constructed wetland in Turkey. It could be originated from the high efficiency of nutrient (nitrogen) removal. Table 2 shows the effluent characterization of the municipal wastewater. It could be said that N_2O emissions positive correlated to TKN concentrations in influent. Influent TKN concentration could increase N_2O emission. In August, at the peak concentration of TKN (85 mg/L), the highest N_2O emission was observed.

Table 3 shows the N_2O emission monitoring results. According to the findings, the highest N_2O emission was released from Zone 1 in August with the value of 11,1367 kg CO_2e/d. It could be considered that N_2O emission would have peak value in summer. The lowest N_2O emission whose value is 4,1356 kg CO_2e/d related to Zone 3 was monitored in January. The minimum nutrient removal rate and the low temperature could be effective on this result.

In the literature, similar results have been obtained by the several researchers on this topic. Han et al. (2019) investigated the influence of plant diversity on greenhouse gas emissions for a vertical constructed wetland. They reported similarly that N_2O emissions parallelly correlated to TKN concentrations in effluent. In this study, similar results were monitored. Recent studies have demonstrated that N_2O can be generated due to several chemical and biochemical processes during nitrification and denitrification. Under aerobic conditions, N_2O production resulting from nitrifier denitrification has been described as the major generation mechanism (Aboobakar et al., 2013). Mander et al. (2014) reported that all of the constructed wetland types demonstrated a significant positive correlation between the inflow TKN loading and N_2O emission values. Mander et al. (2008), Teiter and Mander (2005) and Sovik et al. (2006) monitored N_2O emission from the horizontal subsurface flow constructed wetlands treating domestic wastewater in the range of 0,04-3,01 mg m^{-2} h^{-1}. Van der Zaag et al. (2010) found the N_2O emission as 0.396 mg m^{-2} h^{-1} for *Typha latifolia*. Liu et al. (2009) reported N_2O emission as 0.4 mg m^{-2} h^{-1} for *Phragmites australis*. In contrast with this study, Ruckauf et al. (2004) demonstrated in lab-scale study that Phragmites plants significantly enhanced N_2O emission. Xu et al. (2014) investigated the seasonal variation of GHG emissions from a coastal saline wetland in China. They similarly reported that the highest N_2O emission was monitored in summer and the lowest N_2O emission was monitored in winter. Hernández et al. (2018) performed a similar study. They found that N_2O emissions ranged from 3 to 150 mg m^{-2} d^{-1} with the peak of emission during autumn. Nitrous oxide is generated in the result of nitrification at the aerobic zones and resulting from denitrification at the anoxic zones. From this point of view, it could be said that Zone I has the largest aerobic zones and anoxic zones than the other zones. Also, it could be considered that methane oxidizing bacteria can also be a major player in producing N_2O (Metcalf & Eddy, 2014) especially where methane and nitrogen are abundant.

Results of CH_4 Emissions Monitoring

The horizontal subsurface flow constructed wetlands are one of the significant resources of CH_4 emissions. CH_4 emission could be released from anaerobic zones. CH_4 emissions related to Zone I-III were given in Table 4. According to monitoring results, N_2O emissions were higher than CH_4 emission due to nitrogen uptake of the plants at all zones. CH_4 emissions were higher than CO_2 emissions due to carbon capture of the plants. The highest CH_4 emission was released from Zone I in July. Its value was 1,1781 kg CO_2e/d. The lowest emission was occurred in Zone III in January similar with N_2O emission with the value of 0,4704 kg CO_2e/d. The minimum emission was observed in winter. It could be originated from the low temperatures inhibited the activity of anaerobic bacteria and promoted CH_4 oxidation. From this point of view, it could be said that anaerobic zones and microbial growth (algal growth) could be present much more than other zones. Also, oxygen transfer could be poor in Zone I compared with the other zones.

CH_4 emissions from constructed wetlands were investigated by many researchers. Xu et al. (2014) reported CH_4 fluxes averaged from -0.368 to 4.959 mg CH_4 m^{-2} h^{-1}. They observed the highest emission in autumn. In this study, the highest emission was monitored in summer. It could be originated from those high temperatures enhanced the activities of anaerobic methanogens. A study by Han et al. (2019) was reported that CH_4 emissions ranged between 0,254-0,785 µg/m^2 /day for a lab-scale vertical flow constructed wetland. Chen et al. (2013) similarly investigated CH_4 emission from Yellow River delta wetland. Hernández et al. (2018) reported that 0,71-0,75 mg/m^2 h. conducted a similar study. Methane emission in constructed wetland mesocosms ranged from 0 to 2100 mg/m d, with higher emissions observed at surface flow constructed wetland. Similar with this study, the peaks of methane emission were observed in summer (July-August).

In Table 2, influent carbon concentration in terms of BOD and COD could be seen. It can be said that low organic content wastewater generates low CH_4 emissions. When the low carbon concentration was monitored in January, the lowest CH_4 emission was measured (COD=203,2 mg/L, BOD=80,8 mg/L).

Results of CO_2 Emissions Monitoring

Constructed wetlands play a crucial role on global balance of the major greenhouse gases which are CO_2 and CH_4. They play an important role as a buffer for CO_2 by photosynthetic assimilation and carbon sequestration in the wastewater. A net carbon flux is observed as a result from carbon uptake from the atmosphere by photosynthesis and its release because of decomposition of organic materials at constructed wetlands. Both the rates of carbon uptake and decomposition are affected by climate, nutrient concentrations, water saturation and oxygen availability. In aerobic conditions, decomposition emits CO_2 and CH_4 emissions dominate in anaerobic conditions (IPCC, 2006). Also, CO_2 uptake from atmosphere and dissolved CO_2 from wastewater might be achieved due to photosynthesis. In this study, minor amounts of CO_2 were released from this horizontal subsurface flow constructed wetland. Table 5 shows CO_2 emissions from the wetland. The lowest CO_2 emission was monitored in Zone III with the value of 0,0156 kg CO_2e/d in January. The highest CO_2 emission (0,0363 kg CO_2e/d) was monitored in Zone I in August. CO_2 emission could be originated from the respiration of the microbial community in the constructed wetland. The aerobic microorganisms would be more active in summer. In a study by Chen et al. (2013) investigated the greenhouse gas emission from a wetland. Similar with this study, they found that CH_4 emissions were higher than CO_2 emission. They reported that it could be concluded that CO_2 emission was enhanced by personal activities. Xu et al. (2014) similarly observed higher CO_2 emissions during the summer and autumn seasons. In the literature, CO_2 emission was ignored due to low global warming potential by many researchers.

From Table 2, it could be said that the highest CO_2 emission was released in August in the day of the high effluent BOD and COD concentration. In parallel, the lowest CO_2 emission was generated at the monitoring day of the lowest effluent in terms of COD and BOD concentration.

Effect of Different Plant Species on GHG Emissions

In this study, the effect of *Cyperus esculentus, Typha latifolia* and *Phragmites australis* on GHG emission were investigated. It could be said that N_2O, CO_2 and CH_4 emissions were affected by plant diversity. *Phragmites australis* released the lowest CO_2, CH_4 and N_2O emissions. From this point of view, it could be said that *Phragmites australis* is the best for carbon capture, CH_4 adsorption and N_2O uptake. The results also show that communities with *Phragmites australis* could obtain higher nitrogen removal and lower greenhouse gas emissions than other wetland vegetation. *Phragmites australis* has negative effect on GHG emissions.

Cyperus esculentus is the supply of the highest CO_2, CH_4 and N_2O emission. *Cyperus esculentus* released the largest GHG emission in the wetland. *Typha latifolia* follows it in terms of N_2O and CO_2 emission. Figures (4-6) shows the monthly change of GHG emissions on a plant basis.

Table 2

Influent Characterization at Monitoring Day

Parameter	January	February	March	April	May	June	July	August	September	October	November	December
COD (mg/L)	203.2	440	678	785	888	925	1259	1401,2	1000	645	325	295
BOD (mg/L)	80,8	95	289	380	445	525	690	800,3	603	368	154	101
TKN (mg/L)	66	67	69	70	72	75,5	78	85	83	80	79	69

Table 3

N_2O Emission Monitoring Results

	N_2O Emission (kg CO_2e/d)											
Monitoring Point	January	February	March	April	May	June	July	August	September	October	November	December
Zone I (*Cyperus esculentus*)	9,2859	9,3641	9,3991	9,5359	10,6390	10,8079	10,8371	11,1367	10,7802	10,1375	10,1041	9,6462
Zone II (*Typha latifolia*)	6,1059	6,1841	6,2191	6,3559	7,4590	7,6279	7,6571	7,9567	7,6002	6,9575	6,9241	6,4662
Zone III (*Phragmites australis*)	4,1356	4,1658	4,2930	4,3566	4,4202	4,4520	4,7000	4,7700	4,7659	4,6428	4,5156	4,2860

Table 4

CH_4 Emission Monitoring Results

	CH_4 Emission (kg CO_2e/d)											
Monitoring Point	January	February	March	April	May	June	July	August	September	October	November	December
Zone I (*Cyperus esculentus*)	1,0080	1,0234	1,0300	1,0412	1,1612	1,1756	1,1781	1,1767	1,1424	1,1353	1,0757	1,0737
Zone II (*Typha latifolia*)	0,5040	0,5043	0,5201	0,5241	0,5242	0,5305	0,5373	0,5443	0,5338	0,5326	0,5309	0,5299
Zone III (*Phragmites australis*)	0,4704	0,4744	0,4898	0,4939	0,4969	0,5006	0,5037	0,5040	0,5002	0,4963	0,4937	0,4738

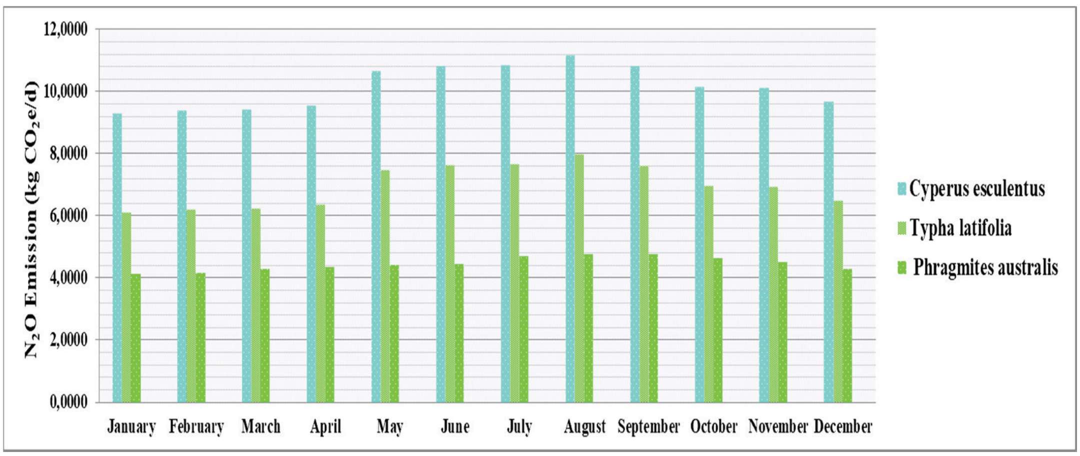
Table 5

CO_2 Emission Monitoring Results

	CO_2 Emission (kg CO_2e/d)											
Monitoring Point	January	February	March	April	May	June	July	August	September	October	November	December
Zone I (*Cyperus esculentus*)	0,0326	0,0335	0,0337	0,0348	0,0349	0,0360	0,0361	0,0363	0,0347	0,0342	0,0345	0,0336
Zone II (*Typha latifolia*)	0,0206	0,0215	0,0217	0,0228	0,0229	0,0240	0,0241	0,0243	0,0227	0,0222	0,0225	0,0216
Zone III (*Phragmites australis*)	0,0156	0,0158	0,0160	0,0161	0,0162	0,0170	0,0171	0,0173	0,0169	0,0168	0,0167	0,0159

Figure 4

Monthly Change of N_2O Emission on a Plant Basis



In this study, global warming potentials of these three plant species were determined using LCA approach. According to the results, *Cyperus esculentus* had the highest global warming potential in the wetland with the value of 3,8 kg CO_2e. *Phragmites australis* had the lowest global warming potential (GWP) in the value of 1,7 kg CO_2e. The global warming potentials of *Typha latifolia* were 2,5. Figure 7 shows the comparison of the global warming potentials. Xu et al. (2014) made the similar study on determination of global warming potential related to *mud flat, S. alterniflora flat, S. glauca flat* and *grass flat*. They used IPCC approach to determine the global warming potentials. They reported that *S. alterniflora* had the maximum global warming potential and *mud flat* had the lowest global warming potential.

Figure 5

Monthly Change of CO_2 Emission on a Plant Basis

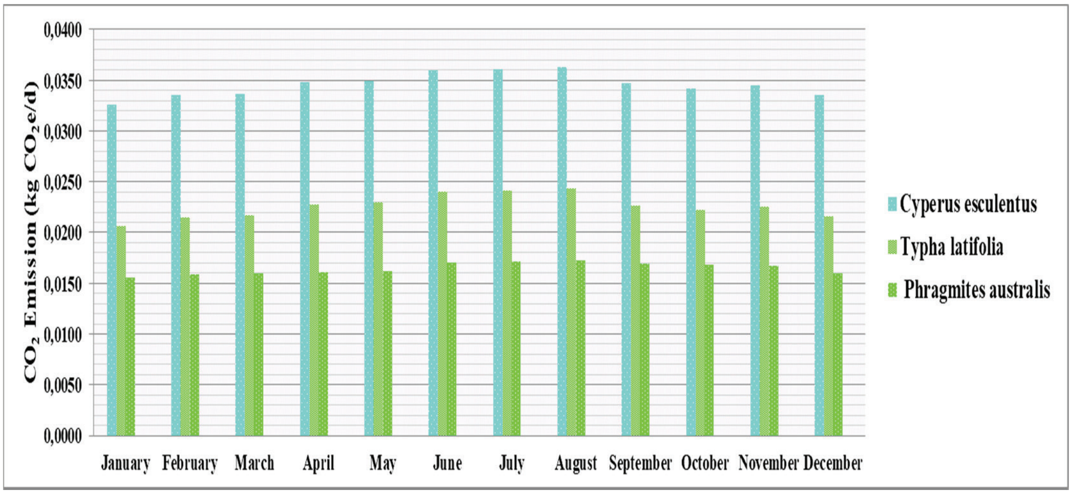
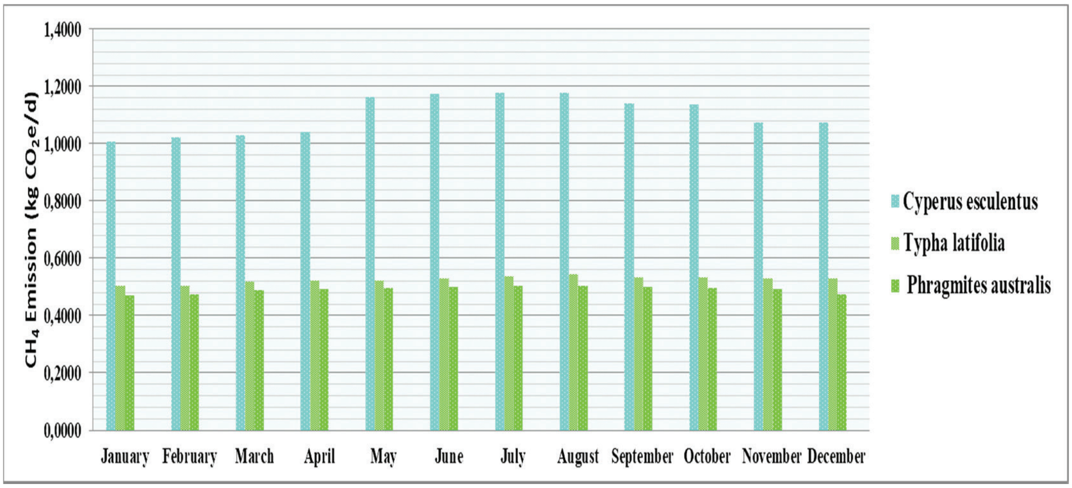


Figure 6

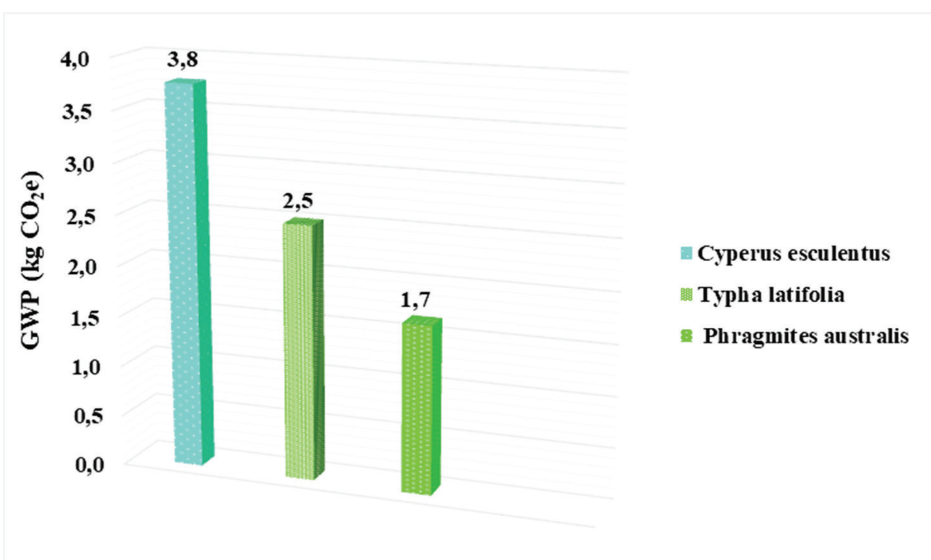
Monthly Change of CH_4 Emission on a Plant Basis



In the literature, similar studies were performed related to other different plant species. Xu et al. (2014) investigated CO_2, CH_4 and N_2O emissions of four different coastal plants which are *mud flat*, *S. alterniflora flat, S. glauca flat* and *grass flat*. They used static chamber method to monitor the GHG emissions. They reported that CH_4 and N_2O emissions were the highest in the *grass flat*, followed by the *S. alterniflora flat*. Higher CO_2 emissions were observed in the *S. alterniflora flat*. This study confirms the result of our study that plant diversity influences GHG emissions. Han et al. (2019) investigated similar influence of plant diversity on greenhouse gas emissions in a vertical constructed wetland. They also reported that the communities with *R. japonicus* presented a decrease in N_2O emissions of 62%. Hernandez et al. (2018) performed a study on greenhouse gas emissions using ornamental plants in a constructed wetland. They reported that plant density had no impact on greenhouse gas emissions in the wetlands planted with *Zhantedeshia aethiopica*. Methane emission was higher in the zones planted with *Zhantedeshia aethiopica* as compared to the zones planted with *Thypha sp* and *Cyperus papyrus*. Chen et al. (2013) investigated the mitigation of GHG emissions in regard to different types of plant species. The plant species, *Phragmites australis,* was similar with this study. The other species were *Beaches bare land, Suaeda salsa, Tamnrix chinesi* and farmland. They reported similar finding with this study that *Phragmites australis* had the lowest CO_2 emission and average CH_4 emission.

Figure 7

Global Warming Potentials of Plant Species



Greenhouse Gas Emission Reduction and Simulation Results

The originality of this work was that Monte Carlo simulation could be applied for the mitigating of GHG emission differently from the other relevant studies in the literature. Table 6 shows the simulation results. The possible GHG emissions were estimated using Monte Carlo simulation if the wetland was vegetated with only *Phragmites australis* at all zones.

Table 6

GHG Minimization Results Using Monte Carlo Simulation

Simulation Point	Total Emission (kg CO_2e/d)	Possible GHG emission (kg CO_2e/d)
Zone I	11,2758	5,9280
Zone II	7,5083	5,0337
Zone III	4,9665	4,9665
Constructed wetland	23,74	15,93

The simulation results showed that overall GHG emission minimization was reached up to 33% if *Phragmites australis* were vegetated at all zones in the horizontal subsurface flow constructed wetland.

Conclusion

This study demonstrated that *Cyperus esculentus*, *Typha latifolia* and *Phragmites australis* could have a significant impact on GHG emissions. It could be considered that N_2O, CH_4 and CO_2 emissions were affected by plant diversity. The highest N_2O emission was released in August at horizontal subsurface flow constructed wetland. The lowest CO_2 emission was observed in January in this constructed wetland. According to the results, *Cyperus esculentus* had the highest global warming potential with the value of 3,8 kg CO_2e. *Phragmites australis* had the lowest global warming potential (GWP) with the value of 1,7 kg CO_2e. The simulation results showed that overall GHG emission minimization was reached up to 33% if *Phragmites australis* were vegetated at all zones in the horizontal subsurface flow constructed wetland.

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Extended Turkish Abstract
(Genişletilmiş Türkçe Özet)

Yatay Yüzey Altı Akışlı Yapay Sulak Alanların Sera Gazı Emisyonlarının Azaltılması

Atıksu arıtma proseslerinden kaynaklanan sera gazı emisyonları, son yıllarda önemli bir çevresel sorun olarak değerlendirilmektedir (Kyung vd., 2015; Gülşen & Yapıcıoğlu 2019). Atıksu arıtma tesisleri uygulanan atıksu arıtma prosesi, çamur işleme ve stabilizasyon prosesleri, kimyasal kullanım, enerji tüketimi ve bakım ve onarım faaliyetlerinden kaynaklı karbondioksit (CO_2), metan (CH_4) ve nitröz oksit (N_2O) olmak üzere üç ana sera gazını salmaktadır. (Rodriguez-Caballero vd., 2014; Kyung vd., 2015). Yapay sulak alanlar, sera gazı emisyonlarını yayan atık su arıtma birimlerinden biri olarak kabul edilmektedir (Mander vd., 2014). Özellikle yapay sulak alanlardan; arıtma prosesi kaynaklı karbondioksit (CO_2), metan (CH_4) ve nitröz oksit (N_2O) emisyonları yayılmaktadır (Mander vd., 2014). Bununla beraber yapay sulak alanlar, son zamanlarda pek çok nedenden dolayı bir sera gazı emisyon azaltma teknolojisi olarak kabul edilmektedir. Yapay sulak alanlarda sera gazı emisyonunu azaltan birçok faktör vardır. Son zamanlarda, yapay sulak alanlardaki bitki türü çeşitliliğinin sera gazı emisyonları üzerinde büyük etkisi olduğu anlaşılmıştır (Han vd., 2019). Bitki türlerinin CO_2, CH_4 ve N_2O'nun üretimi, yayılımı ve taşınmasında büyük farklılıklara neden olduğu görülmüştür (Han vd., 2019). Bu varyasyonlar büyük ölçüde türlerin anatomik özellikleri nedeniyle ortaya çıkmaktadır (Han vd., 2019). Bitki türlerinin çeşitliliği, azot alımını ve karbon tutumunu artırarak CO_2, CH_4 ve N_2O emisyonlarını azaltır. Bitkilerin fotosentez reaksiyonu nedeniyle CO_2, sulak alanda en aza indirilebilir. Bitki türlerinin sera gazı emisyonları üzerindeki etkisi son zamanlarda odaklanılan bir konu haline gelmiştir.

Bu çalışmada, Türkiye'deki bir yatay yüzey altı akışlı yapay sulak alandan salınan sera gazı emisyonları üzerinde farklı bitki türlerinin etkisinin ortaya konması amaçlanmıştır. Yatay yüzey altı akışlı yapay sulak alandan CO_2, CH_4 ve N_2O emisyonları, kapalı çember yöntemi kullanılarak bir yılda toplam on iki kez ölçülmüştür. Ayrıca bitki türlerinin küresel ısınma potansiyelleri (KIP), tüm sera gazı emisyonları dikkate alınarak Yaşam Döngüsü Değerlendirmesi (YDD) yaklaşımı kullanılarak belirlenmiştir. Sera gazı emisyonlarını tahmin etmek için IPCC yöntemine dayalı yeni geliştirilmiş bir model kullanılmıştır. Bu çalışmanın özgünlüğü, yapay sulak alanlar için yeni bir sera gazı emisyon tahmin aracının geliştirilmiş olmasıdır. Bu çalışma, farklı bitki türlerinin etkilerini değerlendirmek için uygulanmıştır. Yatay yüzey altı akışlı yapay sulak alan, sera gazı ölçümü için 3 bölgeye ayrılmıştır. Bitki türü olarak *Cyperus esculentus* (Bölge I), *Typha latifolia* (Bölge II) *ve Phragmites australis* (Bölge III) kullanılmıştır. Bu çalışmanın bir diğer özgünlüğü, *Cyperus esculentus, Typha latifolia* ve *Phragmites australis'in* sera gazı emisyonları üzerindeki etkilerinin, yatay yüzey altı akışlı yapay sulak alan için CO_2, CH_4 ve N_2O emisyonları açısından belirlenmiş olmasıdır. Bu çalışmada literatürdeki ilgili çalışmaların dışında, yeni geliştirilmiş bir sera gazı emisyonu tahmin aracı ile bu üç tür için sadece CH_4 ve N_2O emisyonları değil, aynı zamanda CO_2 emisyonu da ele alınmıştır. Buna ilaveten, bu çalışmanın yeniliklerinden birisi de, sera gazı izleme sonuçlarına dayalı olarak bitki türlerine ilişkin küresel ısınma potansiyellerinin belirlenmesi için YDD metodolojisinin uygulanmasıdır. Çalışmanın son aşamasında, eğer Bölgeler (I-II) en düşük sera gazı emisyonu salan bitki türü ile donatılmış olması durumunda, olası sera gazı emisyonu Monte Carlo simülasyonu kullanılarak tahmin edilmiştir.

Bu çalışmada *Cyperus esculentus, Typha latifolia* ve *Phragmites australis'in* sera gazı emisyonu üzerindeki etkisi araştırılmıştır. N_2O, CO_2 ve CH_4 emisyonlarının bitki çeşitliliğinden etkilendiği söylenebilir. *Phragmites australis* en düşük CO_2, CH_4 ve N_2O emisyonlarını salmaktadır. Bu açıdan bakıldığında, *Phragmites australis*'in karbon yakalama, CH_4 adsorpsiyonu ve N_2O alımı konusunda en efektif bitki olduğu söylenebilir. Sonuçlar ayrıca *Phragmites australis'e* sahip toplulukların diğer sulak alan bitkilerinden daha yüksek azot giderimi ve daha düşük sera gazı emisyonları elde edebileceğini göstermektedir. *Phragmites australis*, sera gazı emisyonları üzerinde azaltıcı bir etkiye sahiptir. *Cyperus esculentus*, en yüksek CO_2, CH_4 ve N_2O emisyonu kaynağı olduğu görülmektedir. *Cyperus esculentus* sulak alandaki en yüksek değerde sera gazı emisyonunu salmıştır. *Typha latifolia* bunu N_2O ve CO_2 emisyonu açısından takip etmektedir. Makalede yer alan şekiller (4-6), bitki bazında sera gazı emisyonlarının aylık değişimini göstermektedir. En yüksek sera gazı emisyonu, Ağustos ayında Bölge I'den salınan N_2O emisyonudur (10,8371 kg CO_2e/d). En düşük emisyon Ocak ayında III. Bölge'deki CO_2 emisyonudur (0,0156 kg CO2e /d). Sonuçlar, *Cyperus esculentus'un* en yüksek sera gazı emisyonuna ve en yüksek küresel ısınma postansiyeline sahip olduğunu ortaya koymaktadır. *Phragmites australis*, en düşük sera gazı emisyonuna ve en düşük küresel ısınma potansiyeline sahip bitki olarak kullanılabilir. Tüm sera gazı emisyonları farklı bitki türlerinden etkilenmiştir. Son olarak, sulak alan sadece *Phragmites australis* ile bitkilendirilmesi durumunda, olası sera gazı emisyonu Monte Carlo simülasyonu kullanılarak tahmin edilmiştir. Sulak alan sadece *Phragmites australisle* bitkilendirilmiş olsaydı, sera gazı emisyonlarında yaklaşık % 33 azalma elde edilebileceği tespit edildi. Bu çalışmada, bu üç bitki türünün küresel ısınma potansiyelleri YDD yaklaşımı kullanılarak belirlenmiştir. Sonuçlara göre *Cyperus esculentus* 3,8 kg CO_2e değeri ile sulak alanda en yüksek küresel ısınma potansiyeline sahiptir. *Phragmites australis*, 1,7 kg CO*2*e değeri ile en düşük küresel ısınma potansiyeline sahip olduğu görülmüştür.