



## Evaluation of the Adaptability, Biomass Yield, and Biofuel Potential of *Miscanthus × giganteus* under Marginal Site

### Marjinal Alan Koşullarında *Miscanthus × giganteus*'un Adaptasyon Yeteneği, Biyokütle Verimi ve Biyoyakıt Potansiyelinin Değerlendirilmesi

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#### Abstract

In this study, the perennial herbaceous C<sub>4</sub> species *Miscanthus × giganteus* was planted using a randomized block design on a low-productivity, idle land located within the boundaries of Kahramanmaraş Sütçü İmam University. Three fertilizer levels 0, 60, and 120 kg ha<sup>-1</sup> were tested within the experimental blocks. Measurements of physiological traits were conducted during the vegetation period in 2015 and 2016. The gas-exchange parameters assessed included net assimilation rate, transpiration rate, stomatal conductance, water-use efficiency, and water potential. Growth-related parameters such as plant height, fresh and dry biomass, and total biomass content (extractive matter, holocellulose ratio, lignin ratio, and ash content) were analyzed. The biofuel production potential was evaluated by calculating the theoretical bioethanol yields and efficiencies from the biomass extracted from *M. giganteus*. The results of this study demonstrate that *M. giganteus*, grown under marginal land conditions, was not significantly affected by increasing fertilizer concentrations or adverse environmental conditions. Moreover, as a non-food energy crop, it successfully avoids the global "food vs. fuel" debate by being independent of the primary food sources relied upon by the world population.

#### Öz

Bu çalışmada, çok yıllık otsu bir C<sub>4</sub> türü olan *Miscanthus × giganteus*, Kahramanmaraş Sütçü İmam University sınırları içerisinde yer alan düşük verimli, atıl bir alanda tesadüf blokları deneme desenine göre ekilmiştir. Deneme parsellerinde 0, 60 ve 120 kg ha<sup>-1</sup> olmak üzere üç farklı gübre dozu uygulanmıştır. Fizyolojik özelliklere ilişkin ölçümler 2015 ve 2016 yıllarındaki vejetasyon dönemlerinde gerçekleştirilmiştir. İncelenen gaz değişim parametreleri; net asimilasyon hızı, transpirasyon hızı, stoma iletkenliği, su kullanım etkinliği ve su potansiyelidir. Bitki boyu, yaş ve kuru biyokütle ile toplam biyokütle içeriği (ekstraktif madde, holoselüloz oranı, lignin oranı ve kül içeriği) gibi büyümeye ilişkin parametreler analiz edilmiştir. Biyoyakıt üretim potansiyeli, *M. giganteus*'tan elde edilen biyokütleden teorik biyoetanol verimi ve verimliliklerinin hesaplanmasıyla değerlendirilmiştir. Bu çalışmanın sonuçları, marjinal arazi koşullarında yetiştirilen *M. giganteus*'un artan gübre dozlarından veya olumsuz çevresel koşullardan önemli ölçüde etkilenmediğini göstermektedir. Ayrıca, gıda dışı bir enerji bitkisi olarak, dünya nüfusunun temel besin kaynaklarından bağımsız olması sayesinde küresel "gıda mı yakıt mı" tartışmasını da başarıyla bertaraf etmektedir.

## INTRODUCTION

The global population growth and technological advancements have significantly increased the demand for natural resources, leading to their near depletion due to uncontrolled exploitation. Consequently, identifying sustainable alternative fuel sources has become critical. Plant-based biofuels, such as vegetable oils, biogas, biomass, and biodiesel, are gaining prominence as viable solutions to the ongoing petroleum crisis (Johansson and McCarthy, 1999; Cao, 2003). These clean, cost-effective, and sustainable energy sources are essential to meet the rising energy needs of an expanding population. As a result, the widespread use of plant-based biofuels is gaining importance. In this context, identifying the most suitable feedstocks for bioethanol production in Türkiye is of critical importance.

Current bioethanol production in Türkiye already far below the required level is carried out using the residues or by-products of agricultural crops such as sugar beet, maize, and barley, which are cultivated on fertile lands primarily for food purposes. This production is secondary in nature and remains significantly lower than Türkiye's projected, committed, and required biofuel output. Therefore, there is an urgent need to conduct research and development in this field, to identify promising options, and to rapidly promote and incentivize their large-scale cultivation across suitable areas.

This study is significant for Türkiye in developing biomass as a key energy source, fostering its industry, and contributing to the national economy. Scientifically, it explores the life cycle, growth, and eco-physiological traits of fast-growing C4 and C3 plants, their soil–plant–water interactions, adaptation to local conditions, and potential to enhance biodiversity. The research specifically evaluates *Miscanthus × giganteus*, a widely studied biofuel crop, under Kahramanmaraş conditions, focusing on its performance on marginal, second-class soils. The study aims to assess its growth, yield, and selected traits while providing practical cultivation guidelines.

When compared with other plant-based feedstocks used in bioethanol production, *Miscanthus* has been shown to yield higher biomass per unit area than most alternative materials. Although some feedstocks such as wheat, rice, and millet can produce higher yields than *Miscanthus*, these crops constitute staple foods for the global population. Therefore, *Miscanthus* offers a distinct advantage over these materials by avoiding the “food versus fuel” conflict (Somerville et al. 2010). The high productivity of *Miscanthus* and its potential as an alternative to wind energy, corn-based ethanol production, and soybean-based biodiesel have been highlighted in numerous studies (Lewandowski et al., 2000; Heaton et al., 2004; Pyter et al., 2007; Heaton et al., 2008; Geren et al., 2011).

Under the European Union's 7th Framework Programme, numerous projects focusing on the testing, cultivation, and conversion of *Miscanthus* into ethanol are being supported (e.g., LED, OPTIMISC).

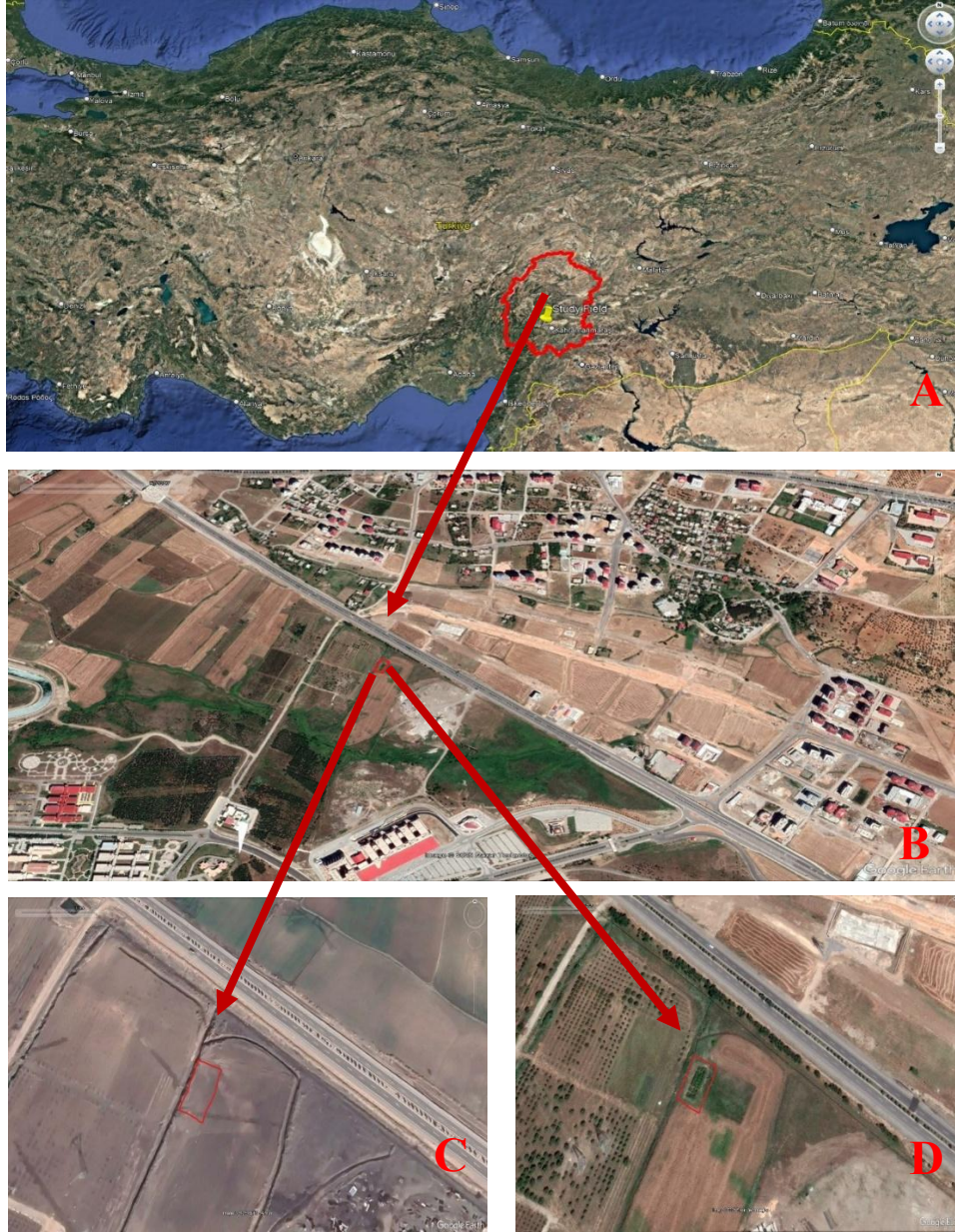
In this study, the aim was to evaluate the growth, development, adaptation, and yield characteristics of *M. giganteus* a species widely investigated and supported in Europe and worldwide for plant-based biofuel production when grown on marginal land not used for agriculture. By assessing its performance on such areas, the study seeks to demonstrate the potential of utilizing *M. giganteus* to make productive use of marginal lands, to avoid the “food versus fuel” conflict associated with certain food crops used for biofuel production, and to contribute to the national economy.

## **MATERIAL AND METHOD**

### **Study Area**

The study was carried out on a marginal area identified within the campus of Kahramanmaraş Sütçü İmam University, which is not suitable for use as agricultural land. The experimental site was selected from a section that does not face protection issues and is not appropriate for agricultural production (Figure 1).

In Kahramanmaraş, where the study was conducted, the lowest temperature in 2014 was recorded as -2.9 °C in February, while the highest temperature was 43.2 °C in August. The month with the highest average precipitation in 2014 was March, with 117.7 mm, whereas the month with the lowest precipitation was August, with 0.8 mm. In 2015 was recorded as -4.7 °C in January, while the highest temperature was 44.5 °C in July. The month with the highest average precipitation in 2015 was February, with 204.6 mm, whereas the month with the lowest precipitation was August, with 3.9 mm (DMİ, 2014; 2015).



**Figure 1.** Satellite images of the *M. giganteus* experimental area in Kahramanmaraş: A) Location of study area on map B) Overview of the experimental area C) Condition of the area prior to sowing D) Vegetation period following *M. giganteus* planting

#### Plant Material

*Miscanthus × giganteus*, a perennial C4 herbaceous plant, was selected for its high photosynthetic productivity, efficient water and nitrogen use, and suitability for marginal lands (Kocaçınar et al., 2010). Rhizomes were sourced from New Energy Farms Group Ltd., Ontario, to evaluate adaptability, biomass yield, and biofuel potential in the study region.



**Figure 2.** *Miscanthus x giganteus* (elephant grass) at the Kahramanmaraş experimental area (Photo: Er L., Person in the photo: Bilgili, O.)

### Experimental Design

The experimental block design was employed for *Miscanthus giganteus* planted in the trial field in this study. Each experimental block consisted of three replicates arranged as plots (Table 1). The *M. giganteus* rhizomes were grown under normal irrigation conditions, and the plots received fertilizer applications of 20:20:20 N:P:K at rates of 0, 60, and 120 (kg ha<sup>-1</sup>). Each clump of *M. giganteus* was spaced at 30 cm, with a 30 cm gap left between clumps. Each plot was arranged to cover an area of 2.5 X 3.5 = 8.75 m<sup>2</sup>, with a 1 m buffer zone maintained between plots. Consequently, a total of 450 *M. giganteus* rhizomes were planted across two experimental designs, covering a total area of 157.5 m<sup>2</sup>.

**Table 1.** Experimental Block for *M. giganteus*

|       | 1. Experimental Block |         |         | 2. Experimental Block |         |         |
|-------|-----------------------|---------|---------|-----------------------|---------|---------|
|       | 3.5m                  | 1m      |         |                       |         |         |
| 2.5 m | 120                   | 0       | 60      | 60                    | 0       | 120     |
|       | 60                    | 120     | 0       | 0                     | 120     | 60      |
| 1 m   | 0                     | 60      | 120     | 120                   | 60      | 0       |
|       | 1. plot               | 2. plot | 3. plot | 1. plot               | 2. plot | 3. plot |

### Gas Exchange and Water Potential Measurements

Leaf gas exchange parameters of *Miscanthus x giganteus* were measured in 2015 and 2016 using a GFS-3000 Model photosynthesis-fluorescence system (Walz, Effeltrich, Germany) during the vegetation period. Measurements, conducted in the morning under open stomata conditions (30–35 °C, ~400 ppm CO<sub>2</sub>, 2000 µE PAR, ~50–55% humidity), recorded net photosynthesis rate (A), transpiration rate (E), stomatal conductance (GH<sub>2</sub>O) and water use efficiency (WUE). In 2016, fresh and dry weights were recorded post-harvest, and leaf water potential was measured using a pressure chamber (PMS Instruments Company, OR, USA). Soil CO<sub>2</sub> flux, moisture, and temperature were monitored at three field locations every 30 minutes over 48 hours using the ACE soil CO<sub>2</sub> exchange system (ADC-Bioscientific, Herts, UK).



**Figure 3.** Physiological Measurements (A) FL3040 Fluorescence head (B) GFS-3000 Portable Gas Exchange System



**Figure 4.** Measurement of Water Potential Using the Pressure Chamber (A) Soil CO<sub>2</sub> Flux Measurement Device (B)

### Soil Analysis

In this study, soil analyses were conducted in June 2014. Soil samples were collected from the field using a random zig-zag method, with three replicates taken from each depth increment, and subsequently submitted to the laboratory for analysis. Soil samples were taken from the experimental site at depths of 0–20 cm, 20–40 cm, and 40–60 cm, and analyzed for saturation, pH, salt content (%), lime content (%), organic matter (%) (Walkley-Black Wet Oxidation Method), potassium (K, mg/kg), and phosphorus (P, mg/kg) (Olsen et al., 1954; Richards, 1954; Grewelling and Peech, 1960; Helmke and Sparks, 1996; Kuo, 1996).

### Lignocellulosic Content Analyses

For lignocellulosic analysis, stem sections measuring 6–8 cm in length were cut from each harvested *Miscanthus giganteus* clump in the field. Each sample was ground in a laboratory-scale Wiley mill according to the TAPPI T 11 m-45 standard (TAPPI 1992) and sieved through 40-mesh (420 micron) and 60-mesh (250 micron) screens. The samples retained on the 60-mesh screen were stored in sealed bags and subjected to chemical analyses to determine the cellulose, hemicellulose, lignin, and ash content.

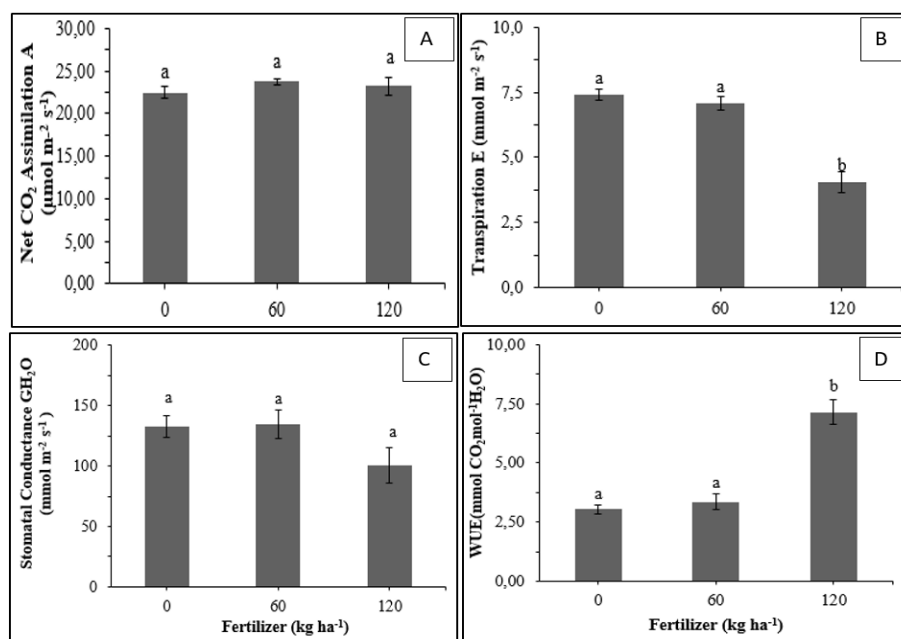
## Statistics

In this study, the data obtained for water potential, photosynthesis rate, transpiration rate, and stomatal conductance were subjected to one-way analysis of variance (ANOVA). Comparisons of differences between measurements were performed using the Fisher LSD comparison test (at a significance level of  $p < 0.05$ ) with the aid of the Sigma-Stat software package (Systat, Chicago, USA)

## RESULTS AND DISCUSSION

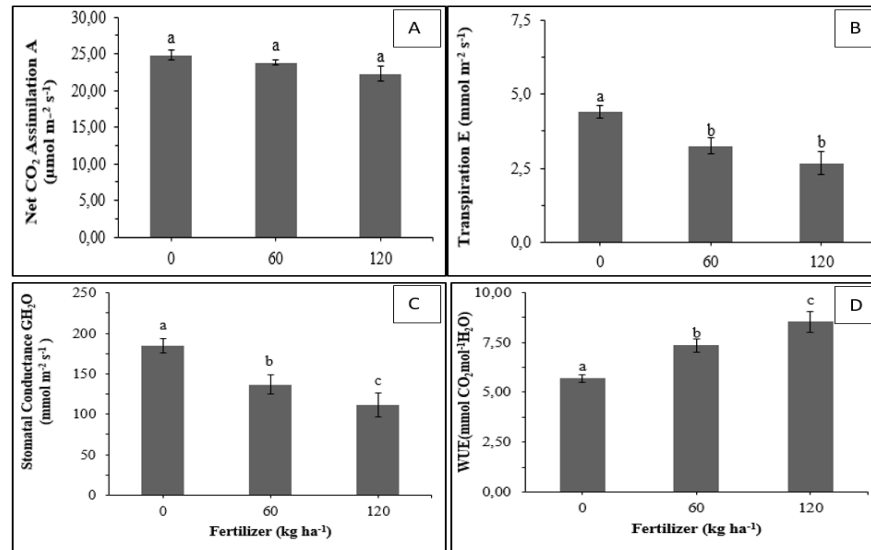
### Gas Exchange Measurements

In September 2015, *Miscanthus × giganteus* net photosynthesis rates averaged 22.46, 23.74, and 23.23  $\mu\text{mol m}^{-2} \text{s}^{-1}$  for 0, 60, and 120  $\text{kg ha}^{-1}$  fertilizer plots, respectively, with no significant differences. Transpiration rates were 7.41, 7.07, and 4.04  $\text{mmol m}^{-2} \text{s}^{-1}$  for 0, 60, and 120  $\text{kg ha}^{-1}$  plots, respectively, with a significant decrease at 120  $\text{kg ha}^{-1}$ . Stomatal conductance was 132.67, 134.31, and 100.80  $\text{mmol m}^{-2} \text{s}^{-1}$  for 0, 60, and 120  $\text{kg ha}^{-1}$  plots, respectively, with no significant differences. WUE values were 3.04, 3.36, and 7.14  $\text{mmol CO}_2 \text{mol}^{-1} \text{H}_2\text{O}$  for 0, 60, and 120  $\text{kg ha}^{-1}$  plots, respectively, with an increase at 120  $\text{kg ha}^{-1}$  (Figure 5).



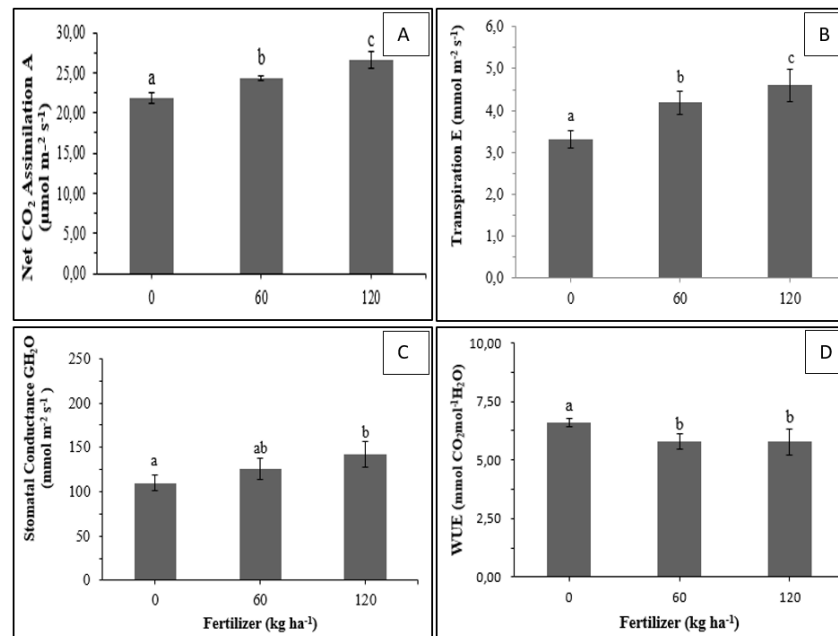
**Figure 5.** September 2015 Net photosynthetic rate (A), transpiration rate (B), stomatal conductance (C) and WUE, (D). Measurements, conducted in the morning under open stomata conditions (30–35 °C, ~400 ppm  $\text{CO}_2$ , 2000  $\mu\text{E PAR}$ , ~50–55% humidity). Bars represent the mean of five different plants, error bars indicate the standard error and different letters denote significant differences

In October 2015, net photosynthesis rates were 24.83, 23.81, and 22.27  $\mu\text{mol m}^{-2} \text{s}^{-1}$ , showing a non-significant decrease with higher fertilizer. Transpiration rates were 4.41, 3.26, and 2.67  $\text{mmol m}^{-2} \text{s}^{-1}$ , showing a significant decline with increased fertilizer.  $\text{GH}_2\text{O}$  values were 184.75, 136.52, and 111.46  $\text{mmol m}^{-2} \text{s}^{-1}$ , decreasing with fertilizer. WUE increased with fertilizer (5.68, 7.34, 8.52  $\text{mmol CO}_2 \text{mol}^{-1} \text{H}_2\text{O}$ ) (Figure 6).



**Figure 6.** October 2015 Net photosynthetic rate (A), transpiration rate (B), stomatal conductance (C) and WUE, (D). Bars represent the mean of five different plants, error bars indicate the standard error and different letters denote significant differences

In July 2016, Photosynthesis rates increased significantly with fertilizer (21.78, 24.29, 26.52  $\mu\text{mol m}^{-2} \text{s}^{-1}$  for 0, 60, and 120  $\text{kg ha}^{-1}$ , respectively). Transpiration rates increased with fertilizer (3.30, 4.19, 4.61  $\text{mmol m}^{-2} \text{s}^{-1}$ ). Stomatal conductance increased with fertilizer (109.92, 125.50, 141.99  $\text{mmol m}^{-2} \text{s}^{-1}$ ). WUE values were 6.60, 5.81, and 5.77  $\text{mmol CO}_2 \text{mol}^{-1} \text{H}_2\text{O}$ , with no significant fertilizer effect (Figure 7).



**Figure 7.** October 2015 Net photosynthetic rate (A), transpiration rate (B), stomatal conductance (C) and WUE, (D). Bars represent the mean of five different plants, error bars indicate the standard error and different letters denote significant differences

In C4 plants, the net photosynthetic rate occurs independently of increasing fertilizer amounts. Although the net photosynthetic rate of C4 plants is not greatly influenced by the amount of fertilizer in the soil, a comparison with a C3 plant shows that the C3 species can respond to the above-mentioned parameters with an increased net photosynthetic rate (Turner and Knapp, 1996). Furthermore, under similar conditions, C4 plants provide higher net carbon assimilation

than closely related C3 species (Kocacinar, 2015). However, because C4 plants have high nitrogen-use efficiency, increasing fertilizer concentration will not have an effect on their net photosynthetic rate (Sage and Pearcy, 1987). In this study, it was observed that varying fertilizer concentrations did not have a significant effect on the net photosynthetic rate.

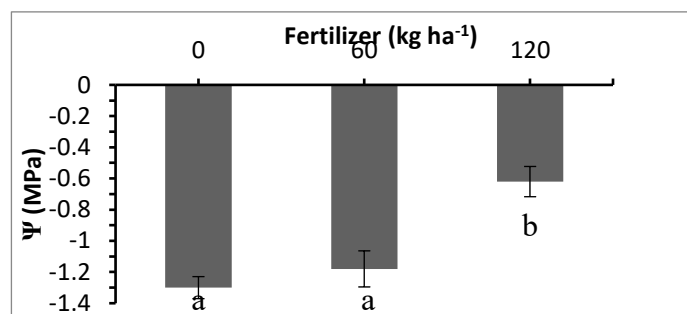
For transpiration rate, as is well known, while the net assimilation rate of a C4 plant is higher than that of comparable C3 plants under the same conditions, its transpiration rate is almost 2–3 times lower (Osborne and Sack, 2012; Kocacinar, 2015). The reason for this is that C4 plants concentrate carbon and consequently narrow their stomatal apertures (Ward et al. 1999). In this study, this trend can be clearly observed (Figure 5-6-7 B). In addition, it can be seen that varying fertilizer treatments did not have a significant effect on transpiration rate.

In this study, *M. giganteus*, a typical C4 species, was found to exhibit low stomatal conductance values (Figure 5-6-7 C). When the effects of varying fertilization levels were evaluated, stomatal conductance was observed to decrease in 2015, whereas in 2016 it increased in direct proportion to fertilization rate. Evaluation of the net photosynthesis rate together with transpiration demonstrated a clear relationship: decreases in photosynthesis were accompanied by decreases in transpiration and stomatal conductance, while increases in photosynthesis resulted in corresponding increases in these parameters. The interannual differences observed are directly associated with the months during which measurements were taken. During July, when temperatures were high, photosynthesis and related physiological parameters increased. In contrast, in September, when temperatures were relatively lower, both photosynthesis and associated parameters declined. These patterns reflect the characteristic temperature response of C4 plants. As temperatures increase, photosynthetic activity and its related physiological processes also increase; at lower temperatures, the opposite trend occurs (Sage and Kubien, 2007; Sage et al., 2010; Kocacinar, 2015).

High water-use efficiency is achieved in all plants when photosynthetic rates are high and transpiration rates are low (Kocacinar and Sage, 2003; Kocacinar and Sage, 2004). Under such conditions, C4 plants exhibit particularly high water-use efficiency (Kocacinar, 2015). Consequently, as a C4 species, *Miscanthus × giganteus* demonstrates strong adaptability in arid and semi-arid environments.

### **Water Potential**

Eco-physiological measurements conducted in July 2016 revealed that the average water potential values for *Miscanthus × giganteus* were -1.3 MPa, -1.18 MPa, and 0.62 MPa for the 0, 60, and 120 kg ha<sup>-1</sup> fertilizer application plots, respectively (Figure 8). Water potential is a good indicator used to determine the severity of drought in plants. A plant having a water potential at negative levels of -1.5 MPa and below indicates that it is under drought stress (Kocacinar and Sage, 2003; Kocacinar and Sage, 2004; Kocacinar, 2015).



**Figure 8.** Water potential of *Miscanthus giganteus* in July 2016. Bars represent the mean of five different plants, error bars indicate the standard error, and different letters denote significant differences

### Biomass Content

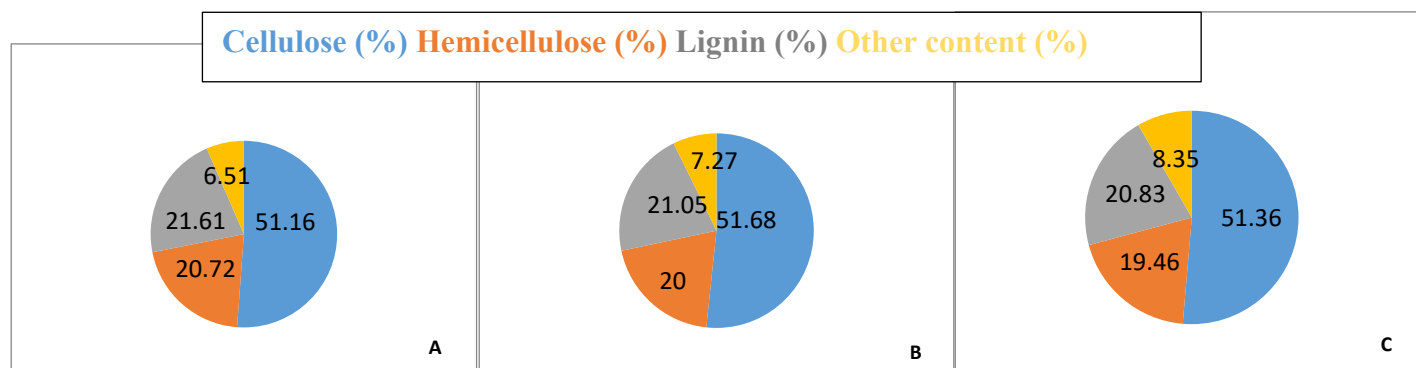
*Miscanthus* has been cultivated by various researchers in different parts of the world under diverse climatic conditions, and its adaptation capacity, biomass production, and biofuel potential have been demonstrated (Lewandowski et al., 2000; Christian et al., 2008; Heaton et al., 2008; Somerville et al., 2010; Tejera et al., 2016). Among these studies, the work of Christian et al. (2008) is noteworthy as it focuses on long-term biomass yield. In this long-term experiment, which lasted approximately 14 years, Christian et al., (2008) examined the growth performance and biomass yield of *Miscanthus × giganteus* in England under fertilizer applications of 0, 60, and 120 kg N ha<sup>-1</sup>. The researchers reported that the yield of *Miscanthus × giganteus* continued to increase after the first year, that the average yield for the first 10 years was 17.7 t ha<sup>-1</sup>, and that the yield of *Miscanthus* as in this thesis study was not significantly affected by increasing fertilizer levels (Christian et al. 2008). Considering all these results, it is understood that the nitrogen requirement of *Miscanthus × giganteus*, a C4 plant, is quite low. This is due to the high nitrogen use efficiency of C4 species; with relatively small amounts of nitrogen, C4 plants are able to maintain high photosynthetic rates and vigorous growth (Sage and Pearcy, 1987).

**Table 2.** Harvest measurements data (January 2016-2017)

| Fertilizer rate (kg ha <sup>-1</sup> ) | January 2016                         |                                    |             | January 2017                         |                                    |             |
|----------------------------------------|--------------------------------------|------------------------------------|-------------|--------------------------------------|------------------------------------|-------------|
|                                        | Fresh weight (ton ha <sup>-1</sup> ) | Dry weight (ton ha <sup>-1</sup> ) | Height (m)  | Fresh weight (ton ha <sup>-1</sup> ) | Dry weight (ton ha <sup>-1</sup> ) | Height (m)  |
| 0                                      | 34.7                                 | 22.8                               | 2.65        | 70.3                                 | 46.1                               | 3.12        |
| 60                                     | 56.83                                | 36.94                              | 3.01        | 70                                   | 47.1                               | 3.64        |
| 120                                    | 59.71                                | 38.34                              | 3.18        | 88.8                                 | 56.9                               | 3.72        |
| <b>Average</b>                         | <b>50.41</b>                         | <b>32.69</b>                       | <b>2.95</b> | <b>76.37</b>                         | <b>50.03</b>                       | <b>3.49</b> |

### Lignocellulosic Content and Determination of Theoretical Biofuel Amount

According to Nigam (2002), the ethanol yield from the dry biomass of raw materials can be approximately estimated by multiplying the holocellulose content (kg) by the theoretical biofuel yield coefficient ( $k=0.444$ ). Accordingly, in this study, the biofuel yield of *M. giganteus* was calculated by determining the amount of holocellulose in the dry matter obtained from the field based on the percentage values presented in Figure 8 and multiplying these values by the theoretical biofuel yield coefficient ( $k=0.444$ ). For example, Somerville et al. (2010), in their calculation based on dry matter, reported results similar to those of this thesis (12 tons of bioethanol from 30 tons/ha of dry biomass). Likewise, Heaton et al., (2008) performed the same calculation for the entire United States. Consequently, the findings of this thesis are consistent with the values reported in these studies.



**Figure 9.** Lignocellulosic Content of *Miscanthus giganteus* at 0 (A), 60 (B), 120 (C) kg ha<sup>-1</sup> fertilizer rate

**Table 3.** Theoretical biofuel yield determination based on dry matter (Nigam 2002)

| Fertilizer Rate<br>(kg ha <sup>-1</sup> ) | Dry Weight<br>(ton ha <sup>-1</sup> ) | Holocellulose Content<br>(ton ha <sup>-1</sup> ) (Cellulose + Hemicellulose) | Theoretical Biofuel Yield<br>(ton ha <sup>-1</sup> ) |
|-------------------------------------------|---------------------------------------|------------------------------------------------------------------------------|------------------------------------------------------|
| 0                                         | 22.85                                 | 16.42                                                                        | 7.29                                                 |
| 60                                        | 36.94                                 | 26.48                                                                        | 11.75                                                |
| 120                                       | 38.34                                 | 27.15                                                                        | 12.05                                                |

### Soil Analysis

Soil samples collected from the field in June 2014, taken in triplicate from depths of 0–20 cm, 20–40 cm, and 40–60 cm, were analyzed in the laboratory to determine their contents. The soil analysis are presented in Table 4. Soil analyses indicate the study site is unsuitable for conventional agriculture, highlighting *M. × giganteus*'s suitability for marginal lands. The average slightly alkaline reaction (pH 7.77) and strong lime content (17.06%) indicate that these two parameters mutually reinforce each other, significantly restricting the availability of micronutrients such as Iron (Fe) and Zinc (Zn) (Marschner, 2012). Furthermore, the soil's critically low average organic matter content (0.60%) (Fageria and Baligar, 2005) is the most significant limiting factor, negatively impacting both soil structure and water holding capacity (Brady and Weil, 2017). An examination of the nutrient balance revealed that Potassium (K) levels are quite high (255.5 mg/kg), whereas the level of available Phosphorus (P) is critically low (2.65 mg/kg); this condition points to the phosphorus fixation problem frequently encountered in high lime soils (Tisdale et al., 1993).

**Table 4.** Soil properties in study field

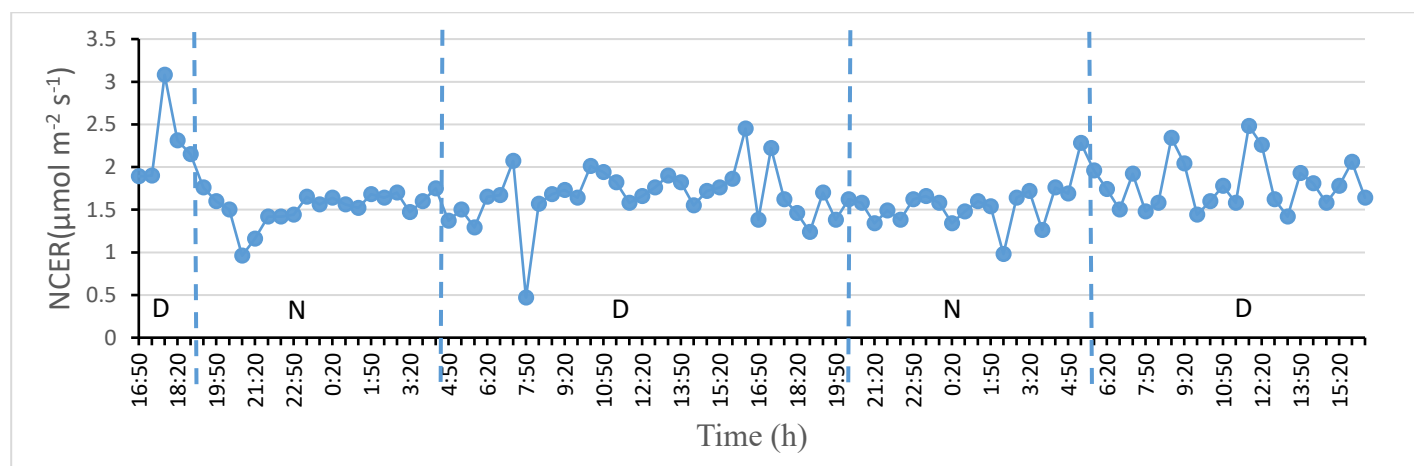
| Depth (cm)     | Saturation (%) | pH          | Salt (%)    | Lime (%)     | Organic Matter (%) | K (mg/kg)    | P (mg/kg)   |
|----------------|----------------|-------------|-------------|--------------|--------------------|--------------|-------------|
| 0–20 (1)       | 59.46          | 7.72        | 0.12        | 15.61        | 0.70               | 275          | 2.95        |
| 20–40 (1)      | 67.5           | 7.79        | 0.13        | 14.94        | 0.56               | 234.1        | 1.61        |
| 40–60 (1)      | 64.06          | 7.81        | 0.11        | 20.63        | 0.54               | 257.4        | 3.41        |
| <b>Average</b> | <b>63.67</b>   | <b>7.77</b> | <b>0.12</b> | <b>17.06</b> | <b>0.60</b>        | <b>255.5</b> | <b>2.65</b> |

### Soil CO<sub>2</sub> Flux Measurement

Soil CO<sub>2</sub> flux, soil moisture, and soil temperature were measured at three representative points in the study area every 30 minutes over 48 hours using the ACE automated soil CO<sub>2</sub> exchange system (ADC-Bioscientific, Herts, UK). Data were categorized into daytime and nighttime averages (Figure 10). Daytime soil CO<sub>2</sub> flux averaged 1.77 μmol m<sup>-2</sup> s<sup>-1</sup>, with a soil

temperature of 32.86 °C and soil moisture of 68.57%. Nighttime flux averaged 1.51  $\mu\text{mol m}^{-2} \text{s}^{-1}$ , with a soil temperature of 23.20 °C and soil moisture of 66.88%. Soil CO<sub>2</sub> flux (0–3  $\mu\text{mol m}^{-2} \text{s}^{-1}$ ) suggests low organic matter and slow decomposition, typical of arid soils, limiting suitability for conventional agriculture or forestry (Moussadek et al., 2011). The soil CO<sub>2</sub> flux (NCER) findings suggest that the biological activity of the field is moderate and comparable to that of temperate agricultural lands, yet this activity demonstrates a strong dependence on soil temperature. The difference between the average daytime flux (1.77  $\mu\text{mol m}^{-2} \text{s}^{-1}$ ) and the nighttime flux (1.51  $\mu\text{mol m}^{-2} \text{s}^{-1}$ ) confirms that the significant increase in temperature ( $\Delta T \approx 9.66^\circ\text{C}$ ) accelerates both root and microbial respiration at an exponential rate, thus aligning with the general ecological principle that flux is controlled by temperature (Lloyd and Taylor, 1994). The observed values, ranging between 1.5 and 1.8  $\mu\text{mol m}^{-2} \text{s}^{-1}$ , fall within the range commonly reported in the literature for temperate and semi-arid agricultural ecosystems (1.0 to 3.5  $\mu\text{mol m}^{-2} \text{s}^{-1}$ ) (Raich and Schlesinger, 1992).

This suggests that despite the field's very low organic matter content, the existing carbon pool is being moderately and continuously mineralized under favorable temperature and moisture conditions. These findings indicate that the current biological respiration is sensitive to temperature shifts and point to the potential for anticipated temperature increases in climate change scenarios to augment carbon efflux.



**Figure 10.** Soil CO<sub>2</sub> Flux in the experimental field over 48 hours

## CONCLUSION

This study assessed the eco-physiological performance of *Miscanthus × giganteus* on marginal, semi-arid lands with high groundwater levels. As a non-food C4 energy crop, *M. × giganteus* exhibited strong adaptability, with minimal fertilization sufficient for robust growth due to its high nitrogen use efficiency compared to C3 plants. Dry matter yield surpassed that of many energy crops, even under marginal conditions, and theoretical bioethanol yield was superior to other studied crops. Grown on non-arable land, *M. × giganteus* avoids the "food vs. fuel" debate, making it a cost-effective bioenergy source with significant potential to contribute to the national economy.

This study evaluated eco-physiological measurements conducted on the energy crop *Miscanthus giganteus* cultivated in a marginal field, characterized by high groundwater levels and semi-arid conditions during the growing season. The assessment focused on the plant's adaptability, eco-physiological responses to these limiting conditions, and yield parameters. Analysis of different fertilization rate blocks revealed that increasing nutrient concentrations did not

significantly contribute to the plant's performance; minimal fertilization proved adequate for effective and high-yielding cultivation.

This outcome suggests that the C4 *M. giganteus* inherently possesses high physiological efficiency in utilizing available resources. Consequently, the plant demonstrated superior performance in terms of physiological adaptability and biomass production even at low input levels. The measured dry matter yield per hectare for *M. giganteus* was found to be higher than that of many other perennial energy crops documented in the literature, even when grown under marginal constraints. Furthermore, theoretical analysis confirmed that *M. giganteus* offers a higher potential for bioethanol conversion compared to other common bioenergy feedstocks. Considering these results, and noting that the crop is grown on non-agricultural, marginal land (thereby avoiding the "food vs. fuel" conflict), it is strongly recommended that *M. giganteus* be adopted for large-scale biomass and bioethanol production. Its high efficiency and low input requirement promise significant cost reduction and value creation for the national economy.

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