

Influence of biochar on soil physicochemical traits and *Triticum durum* L. physiology during abiotic stress ¹

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Abstract

Improving soil nutrient reserves through effective land management practices and pasture utilization is a continuing focus in agricultural discussions. Among the various methods aimed at boosting crop productivity, the use of mineral or organic fertilizers is prominent. Biochar, a carbon-rich substance derived from the pyrolysis of organic residues, is commonly employed as a soil amendment to enhance fertility and improve soil characteristics. This study aims to evaluate the impact of biochar on soil physicochemical properties and the yield of a vital forage crop: durum wheat. Three different doses of biochar were applied (D0 = 0g of biochar, D1 = +20g/pot, and D2 = +60g/pot), in conjunction with two types of water and salt stress. Water stress levels were categorized into four stages (S1 = 100%, 80%, 40%, and 20% of field capacity), while salt stress was administered at three varying concentrations: S0 = 0g of NaCl/l, 4g of NaCl/l, and 9g of NaCl/l. The results indicate an increase in pH (7.77) and electrical conductivity (1369.13 μ S/cm), accompanied by a noticeable improvement in nitrates (7.36 mg/g of soil). Significant increases were also observed in total carbon (2.83%) and soil moisture (8.81%), along with a substantial accumulation of active limestone (3.60%). The plant's response to biochar was particularly notable, especially in terms of chlorophyll levels (3.88 μ g/g FW) and leaf water content (45.54%).

Keywords: Biochar, durum wheat, soil fertility, drought stress, salt stress.

Influence du biochar sur les propriétés physico-chimiques du sol et sur la physiologie du *Triticum durum* L. sous stress abiotique

Resumé

L'amélioration de la gestion des terres agricoles et des prairies pour accroître les réserves nutritives dans le sol suscite un intérêt grandissant. Parmi les méthodes envisagées pour augmenter les rendements des cultures, l'utilisation d'engrais minéraux ou biologiques est souvent privilégiée. Le biochar, un matériau carboné produit par la pyrolyse de déchets organiques, est largement utilisé pour enrichir le sol et en améliorer les caractéristiques. Cette étude vise à évaluer l'impact du biochar sur les propriétés physico-chimiques du sol et sur la production d'une plante fourragère, le blé dur. Trois doses de biochar ont été appliquées (D0 = 0 g de biochar, D1 = +20g/pot et D2 = +60g/pot), combinées à deux types de stress, hydrique et salin. Pour le stress hydrique, quatre niveaux ont été testés (S1 = 100%, 80%, 40%, et 20% de la capacité au champ). Le stress salin a été induit à trois doses : S0 = 0g de NaCl/l, 4g de NaCl/l et 9g de NaCl/l. Les résultats révèlent une augmentation du pH (7.77) et de la conductivité électrique (1369.13 μ S/cm), ainsi qu'une amélioration des niveaux de nitrates (7.36 mg/g de sol). Une augmentation significative du carbone total (2.83%) et de l'humidité (8.81%) du sol a également été observée, ainsi qu'une forte accumulation de calcaire actif (3.60%). La réponse de la plante au biochar était plus prononcée, notamment en ce qui concerne la chlorophylle (3.88 μ g/g MF) et la teneur relative des feuilles en eau (45.54%).

Mots clés : Biochar, blé dur, fertilité du sol, stress hydrique, stress salin

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INTRODUCTION

In the arid and semi-arid areas of Algeria, soils are often described as skeletal due to harsh climatic conditions, including scant rainfall, high temperatures and overgrazing (Manya et al., 2012). This situation led to a significant decline in agricultural productivity and a reduction in the reserves of mineral and organic matter in the soil, thus making it infertile. In response, many farmers have turned to the use of chemical fertilizers to improve soil fertility, despite their high cost (Lehmann et al., 2011). In the region of Tébessa, where poultry farming is dominant, spreading poultry manure on the ground is a common practice to replenish mineral reserves, particularly nitrogen, essential for plant growth (Revell et al., 2012). However, some farmers have reported a decrease in productivity over the years, possibly due to low

carbon and high sodium concentration in manure (Manya et al., 2012). Therefore, it has become essential to restore soil fertility using other types of fertilizers (Liu et al., 2016).

Biochar has attracted attention in recent years as a promising amendment for sustainable agriculture (Antal and Gronli, 2003). Compared to crop residues or poultry litter, biochar stands out for its high carbon content (Manya et al., 2012). It has been reported to improve soil physical properties, such as porosity, water holding capacity, stability and aggregate formation (Ding et al., 2010). However, the effects of biochar can vary, and the response of plants to this amendment depends on its composition, soil type and specific crop needs (Watts et al., 2005).

MATERIAL AND METHODS

1. The origin of biochar

As part of this study, we initiated the biochar production process by collecting wheat straw, barley, sawdust and tree leaves, which we then introduced into a container. Subsequently, these materials were ignited inside the container, containing vehicle oil, before hermetically sealing the container to exclude oxygen during the pyrolysis process of organic waste. This method resulted in obtaining biochar.

2. Experimental apparatus

The objective is to evaluate the impact of the biochar amendment, applied at different doses, in conjunction with water and saline deficit treatments, on the physicochemical characteristics of the soil and the production of durum wheat.

The tests were carried out in plastic pots with a uniform capacity of 3 kg. Three factors were taken into account:

The first factor concerned the water regime applied to the plants, including water levels varying from 100% to 20% of field capacity.

The second factor was salt stress, established at three levels of NaCl concentration (0 - 1.4 - 9 g/l).

The third factor was the biochar amendment, administered at three different doses: D0 without biochar (control), D1 with 20g of biochar per pot, and D2 with 60g of biochar per pot. The soil used to fill the pots came from the study region. Prior to the experiment, both the soil and the biochars were subjected to chemical analysis to determine their physical and chemical properties, the details of which are presented in Table 1

Table 1: Characteristics of used soil and biochar.

Parameter	Soil	BIOCHAR
pH	7.17 ± 0.30	8.96
EC µS/cm	583 ± 116.76	1320 ±192.87
Active limestone %	-	4.66 ± 0.45
Limestone Total %	-	14.34 ± 1.87
Total carbon %	0.9	7.88 ± 0.25

Sowing was carried out in each pot with 07 seeds of durum wheat (*Triticum durum*) variety Vitron, coming from the OAIC of Tébessa. The grains were carefully watered, and the pots were placed in the greenhouse. The application of biochars was carried out simultaneously with sowing.

Irrigation monitoring was carried out taking into account the field capacity of the soil, which was determined at the start of the experiment. The application of water stress, combined with salt stress according to the levels mentioned previously, was initiated after a period of 30 days, corresponding to the phase where the plants developed four leaves.

3. Physico-chemical parameters of the soil

The soil physicochemical parameters studied included:

- Soil pH, measured according to the method described by Pieltain and Mathieu (2003).
- The electrical conductivity (EC) of the soil, also determined according to the protocol of Pieltain and Mathieu (2003).
- Soil moisture, assessed according to the method described by Baize and Jabiol (1995).
- The level of active limestone in the soil, measured using the Baize method (2000).
- The level of total limestone present in the soil, also evaluated according to the Baize protocol (2000).
- The total carbon rate in the soil, determined using the Walkley-Black method (1934) and in

accordance with the recommendations of Pieltain and Mathieu (2003).

- The dosage of nitrates in the soil, carried out according to the protocol of Rodier et al. (1986).

4. Chlorophyll pigment content

The extraction of chlorophyll a and b is carried out according to the method of **Burnison 1980**

5. Relative water content

The relative water content (RWC) was determined using the following technique: Three leaves were taken from each pot and their fresh weight was measured. These leaves were then immersed in distilled water for 24 hours to obtain their turgor weight and then dried to obtain their dry weight. The RWC was calculated according to the following formula, established by Barrs (1968):

$$RWC = \frac{FW - DW}{TW - DW} \times 100$$

DW: dry weight, FW: fresh weight, TW: turgor weight.

6. Statistical analysis

The results obtained were subjected to a two-way analysis of variance (ANOVA). The first factor corresponds to the effect of biochar treatment, while the second factor represents the effect of stress. For parameters for which a significant effect was observed, a means

comparison test was performed using the Tukey HSD test.

RESULTS AND DISCUSSION

1. Soil parameters

1.1. pH

The pH results reveal a highly significant effect for both the biochar treatment ($F=53.1$; $P<0.00001$) and the stress effect ($F=2.8$;

$P=0.004$), as well as the interaction between stress and treatment ($F=5.2$; $P<0.000001$). It is observed that the biochar treatment induced a linear increase in pH with the applied doses. The value measured with dose D1 (8.80) exceeds that of dose D2 (7.68), and finally that of dose D0, noted at 7.40 (Figure 1).

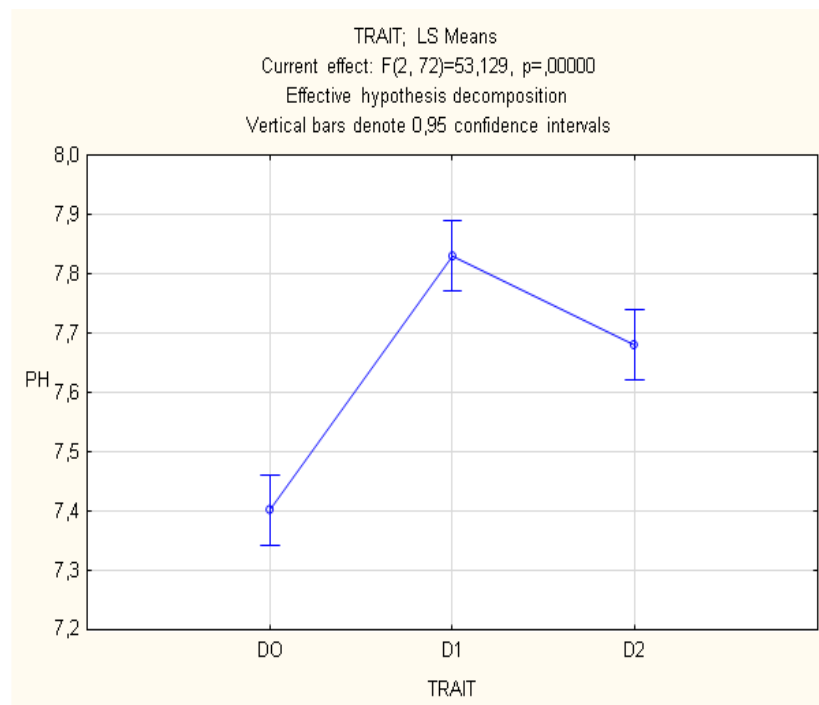


Figure 1: Effect of biochar treatment on soil pH .

The Tukey HSD test reveals that stress leads to the formation of two distinct groups, the highest value being obtained with the H3S1

level (7.77), while the lowest value is observed with the H2S2 stress level (7.47).) (Figure 2).

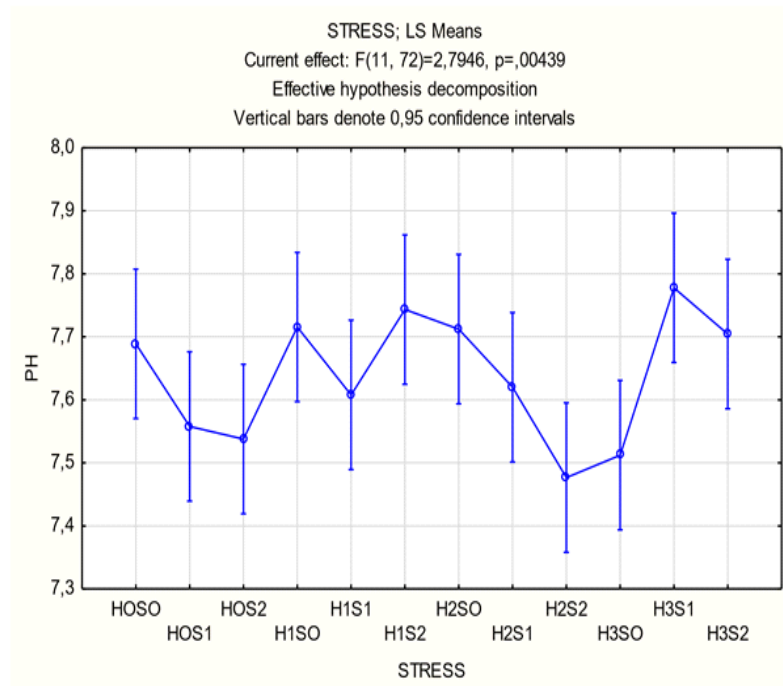


Figure 2: Effect of stress on soil pH .

It is also observed that the joint application of stress and biochar results in an increase in pH, an increase that is more pronounced with doses D1 and D2 (Figure 3).

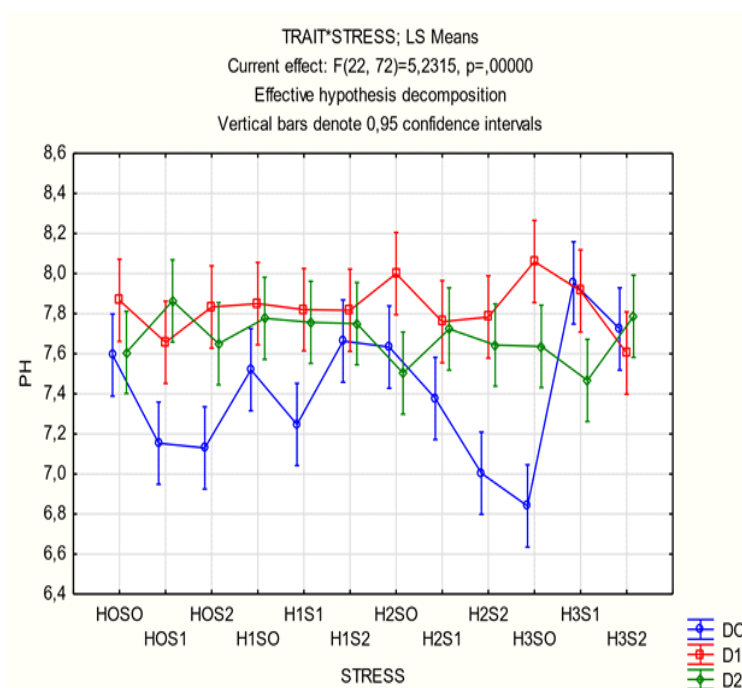


Figure 3: The stress*treatment interaction effect on soil pH.

1.2. Electrical conductivity

Analysis of variance of electrical conductivity reveals that the addition of biochar has a highly significant effect ($F=33.62$; $P<0.000001$), as does the effect of stress ($F=106.28$; $P<0.000001$). In addition, a significant interaction between stress and

treatment is observed ($F=36.05$; $P<0.000001$). Biochar application resulted in an increase in electrical conductivity (EC) from the value of $1199.16 \mu\text{S}/\text{cm}$ to the highest value of $1369.13 \mu\text{S}/\text{cm}$ for dose D2 (Figure 4).

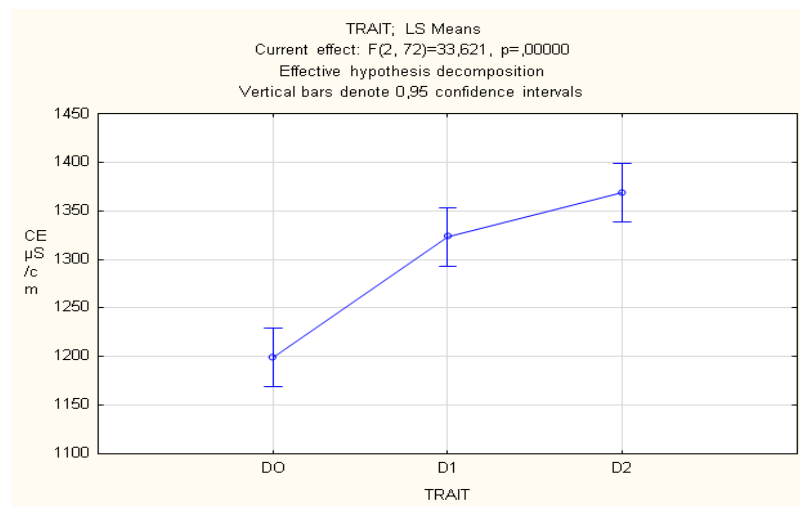


Figure 4: Effect of biochar treatment on soil electrical conductivity .

The joint application of water and salt stress resulted in a significant increase in electrical conductivity (EC), especially with the highest water and salt stress levels. The Tukey HSD test shows five distinct groups, where the lowest EC is attributed to water stress levels H0S0 and H3S0. However, when water stress is combined

with salt stress, the EC reaches very high values, these levels being grouped into a higher category. The highest EC value is observed with the H1S2 level ($1709.11 \mu\text{S}/\text{cm}$), while the H3S2 level displays an EC of $1416.77 \mu\text{S}/\text{cm}$ (Figure 5).

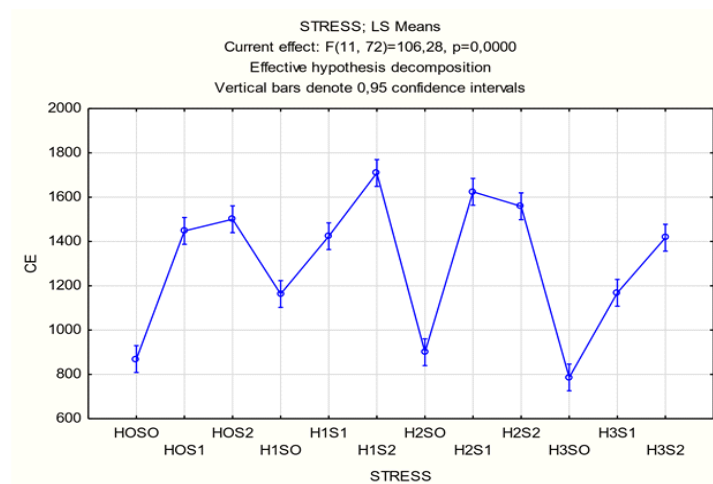


Figure 5: Stress * treatment interaction effect on soil electrical conductivity .

Regarding the interaction, the results show that the more severe the stress level becomes, the more pronounced the increase in

electrical conductivity (EC), in relation to the doses of biochar applied (Figure 6).

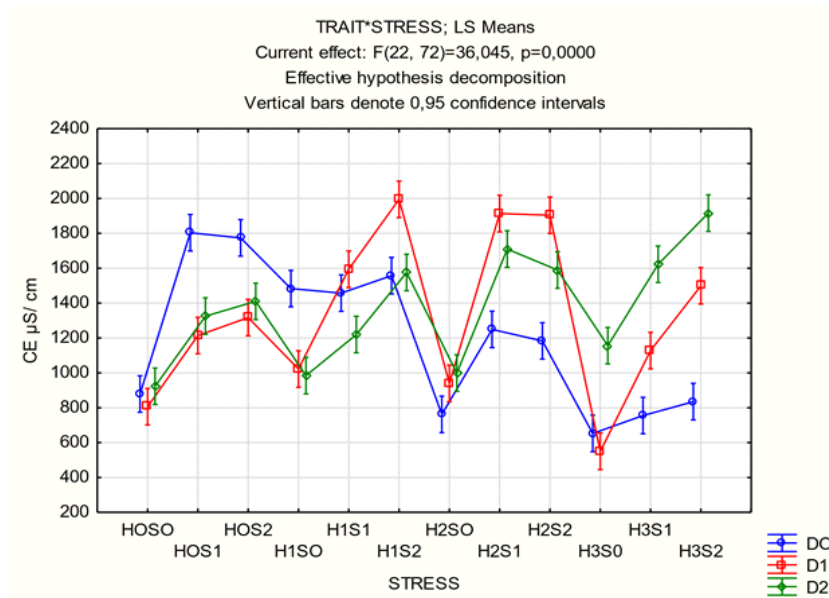


Figure 6: Stress* treatment interaction effect on soil electrical conductivity .

1.3. humidity

Statistical analysis reveals a significant effect of treatment ($F=6.143; P=0.003$), as well as a significant effect of applied stress ($F=3.39; P=0.0008$). In addition, a highly significant interaction between stress and treatment is observed ($F=3.91; P<0.00001$).

The results obtained indicate an improvement in humidity with increasing application of biochar doses (Figure 7). With dose D1, a humidity rate of 8.81% is obtained, followed by 8.53% with dose D2, and finally a rate of 7.70% for the last group, D0.

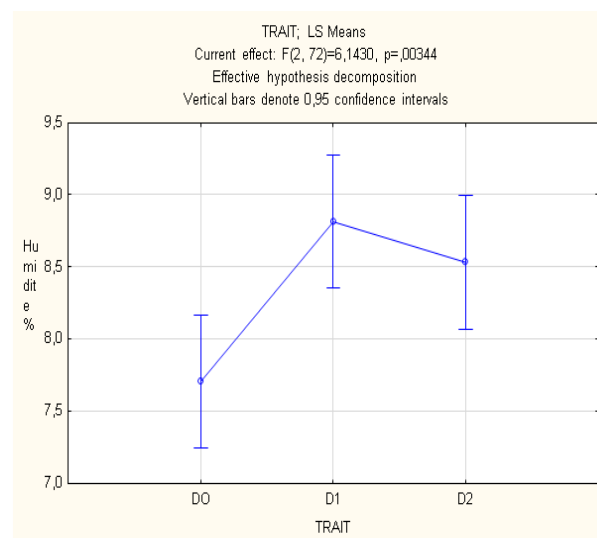


Figure 7: Effect of biochar treatment on soil moisture.

Humidity decreases in response to the application of stress (Figure 8). Notably, the lowest humidity recorded, i.e. 9.39%,

corresponds to the highest stress levels, particularly at the H3S2 level combining water and saline stress.

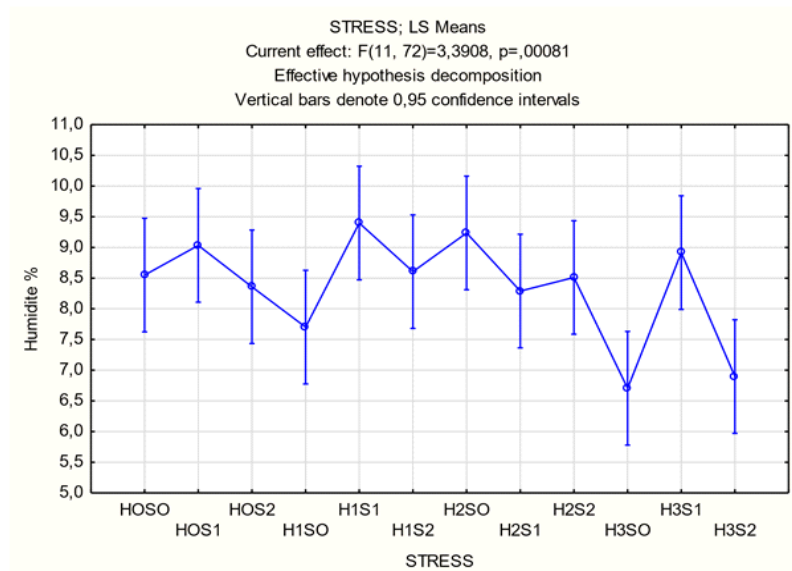


Figure 8: Effect of stress on soil moisture.

It is also observed that humidity increases with the application of biochar doses,

in parallel with increasing applied stress levels (Figure 9).

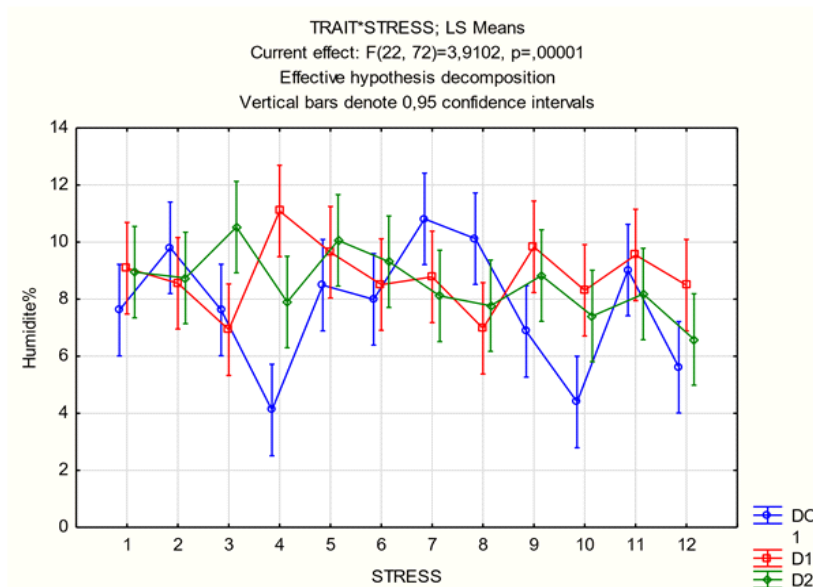


Figure 9: Effect of stress*treatment interaction on soil moisture .

1.4. Active limestone

Analysis of variance for active limestone reveals a significant increase due to

soil amendment with biochar ($F=202.28$; $P<0.000001$). Three distinct groups are observed, the first being the D2 dose with the

highest value of 3.66%, followed by the D1 group with a content of 3.14%, and finally the

last group represented by the D0 dose (the control) with a value of 2.63% (Figure 10).

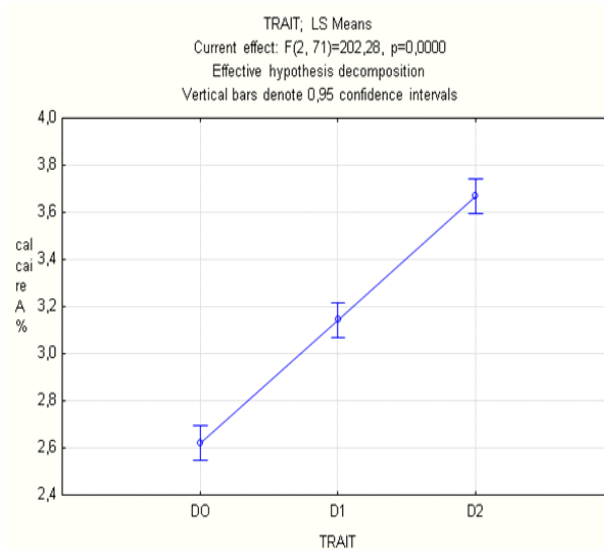


Figure 10: Effect of biochar treatment on active limestone content.

The statistical analysis highlights the very strong significance of the effect of stress (F=13.20; P<0.000001), as well as the interaction between stress and treatment (F=6.62; P<0.00001). The results reveal that stress divides the samples into six distinct

groups, where the maximum value of active limestone is recorded with the H2SO stress level (3.60%), while the minimum value is recorded with the H0S1 stress level at 2.88% (Figure 11).

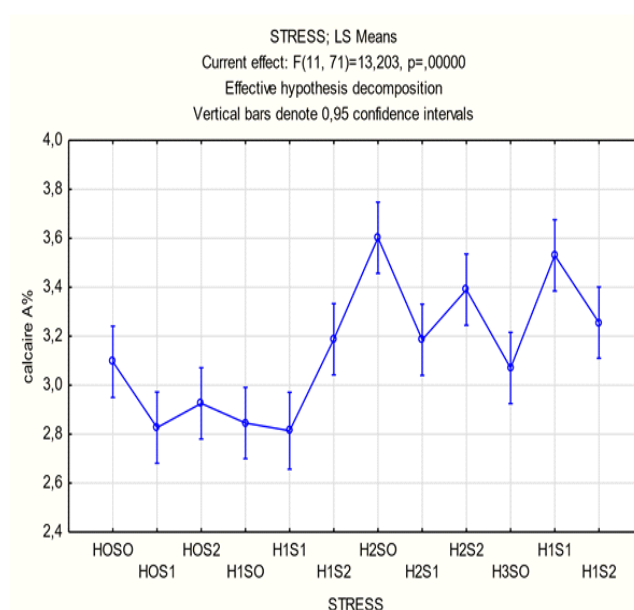


Figure 11: Effect of stress on the active limestone content of the soil.

The interaction between the treatments highlights a notable accumulation of active limestone, mainly observed with the D2 level. This accumulation is particularly significant

with the H3S2 and H3S1 stress levels, where the respective values are 3.25% and 3.53% (Figure 12).

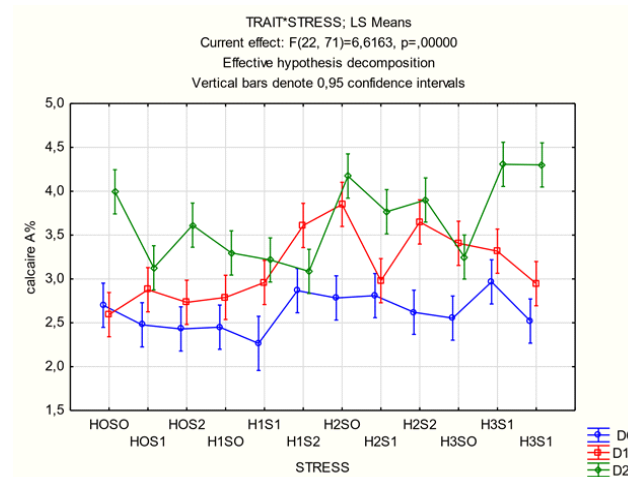


Figure 12: Stress * treatment interaction effect on the active limestone content of the soil .

1.5. Total limestone

The evolution of total limestone reveals a highly significant effect of the biochar treatment ($F=132.25$; $P<0.000001$), as well as a significant effect of stress ($F=4.32$; $P<0.000001$) and the interaction between stress and treatment ($F=5.66$; $P<0.000001$).

The Tukey HSD test indicates that the biochar treatment is divided into three distinct groups (see Table 14 in the appendix). Dose D0 (control) presents the highest value in total limestone, with 15.65%, followed by dose D2 with 13.28%, and finally dose D1 with 8.77% (Figure 13).

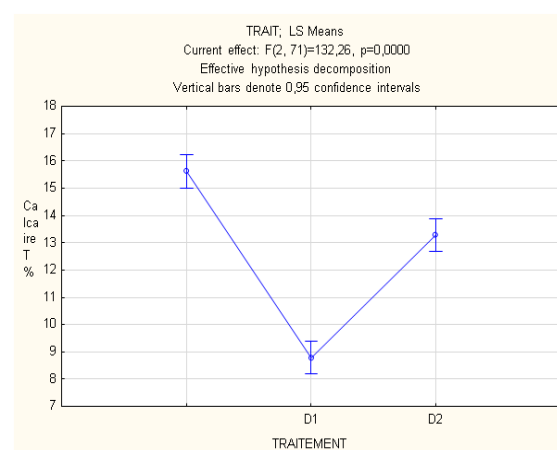


Figure 13: Effect of biochar treatment on total limestone content .

The effect of stress revealed three distinct groups for this parameter, with the highest value in total limestone reaching

15.50%, observed at the H2SO level. On the other hand, the lowest content was attributed to the H3S2 stress level, with 10.82% (Figure 14).

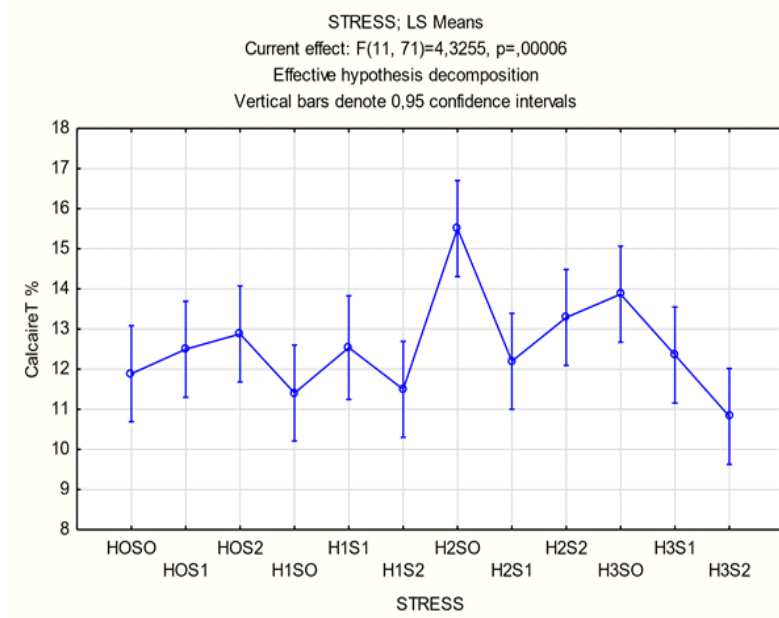


Figure 14: Effect of stress on the total limestone content of the soil .

The interaction also reveals that the biochar treatment level has the highest values, followed by doses D2, then D1. The average comparison test thus indicates that the highest

content is obtained with the H3SO level, at 13.86%, while the lowest is observed with the H3S1 level, at 12.35% (Figure 15).

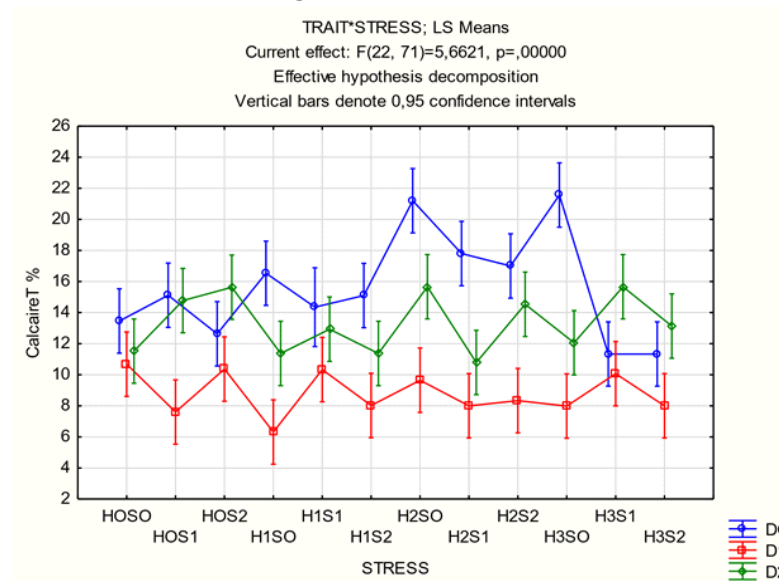


Figure 15: Effect of the stress*treatment interaction on the total limestone content of the soil .

1.5. Total carbon

The statistical analysis of carbon reveals a significantly positive evolution under the effect of the treatment ($F=1068.33$; $P<0.000001$). Likewise, the effect of stress is also significant ($F=4.54$; $P<0.00003$). Concerning the interaction between stress and

treatment, a similar trend was observed ($F=4.69$; $P<0.000001$).

The Tukey HSD test for biochar treatment highlights three distinct groups, with an ordering of $D0<D1<D2$ values. The values obtained with $D0$ (1.81%) and those with $D2$ (2.83%) are illustrated in Figure 16.

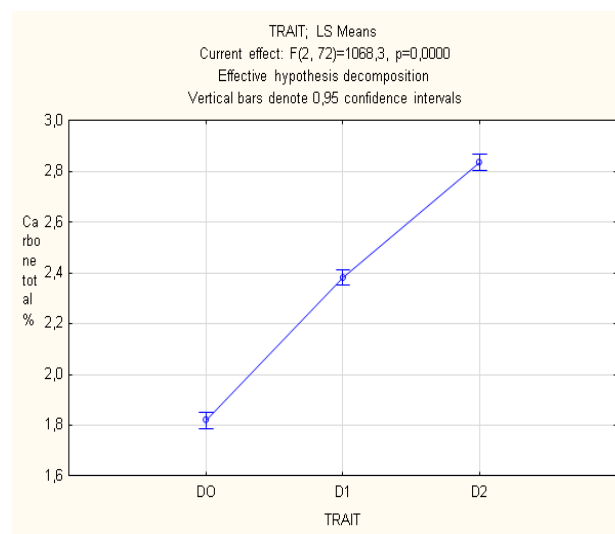


Figure 16: Effect of biochar on the carbon content in the soil.

The application of stress influences soil carbon composition. The average comparison test highlights three groups, with the highest

value of 2.44% attributed to the H1S1 level, and the lowest content of 2.24% observed at the H3S1 level (Figure 17).

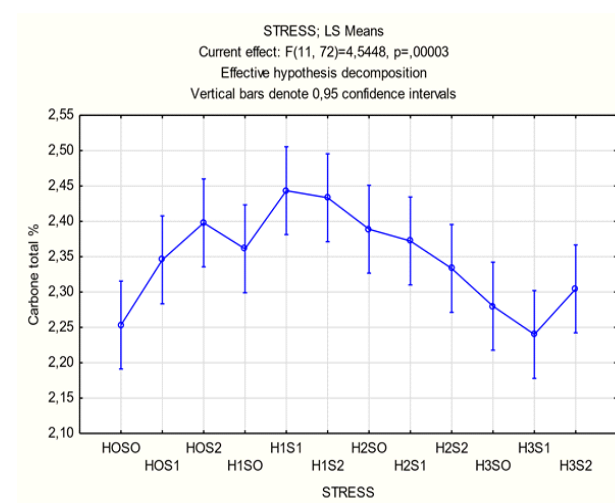


Figure 17: Effect of stress on soil carbon content.

Stress combined with biochar application promotes maintenance of soil carbon levels higher than those in the control soil (Figure 18).

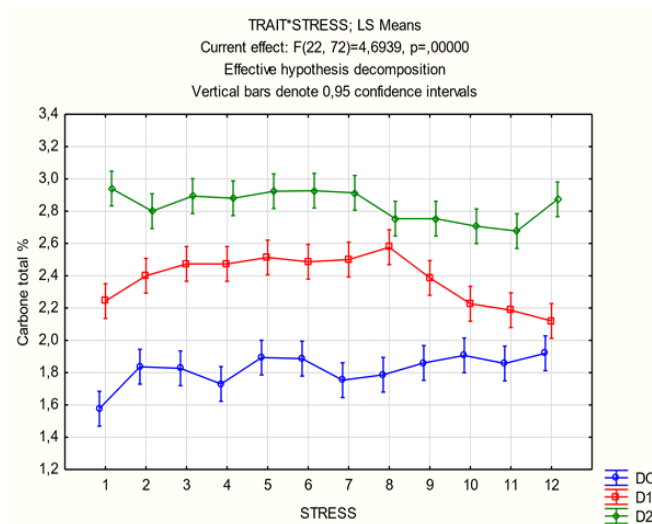


Figure 18: The stress*treatment interaction effect on the carbon content in the soil .

1.6. Nitrates

The analysis of variance (ANOVA) concerning the nitrate content in the soil reveals a highly significant treatment effect ($F=575.54$; $P<0.00001$). Similarly, the application of stress resulted in a highly significant effect ($F=5.21$; $P<0.00001$) on the nitrate content in the soil, as

did the interaction between stress and treatment ($F=5.18$; $P<0.00006$).

Biochar promoted a significant accumulation of nitrates in the pots receiving dose D1 (7.36 mg/g of soil), while doses D2 and D0 recorded 3.27 mg/g and 3.14 mg/g of soil, respectively (Figure 19).

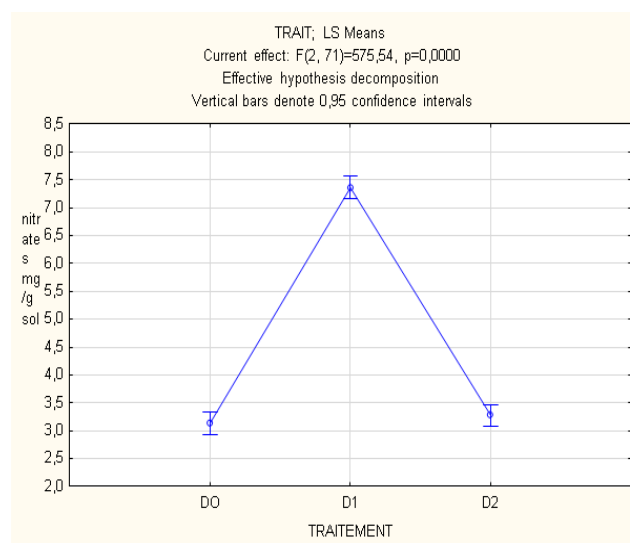


Figure 19: Effect of biochar treatment on soil nitrate content.

With the application of stress, we distinguish three groups, where the highest value is observed at the H3SO level (5.38 mg/g

of soil), while the lowest content is recorded at the H2S1 level (3.77 mg/g of soil) (Figure 20).

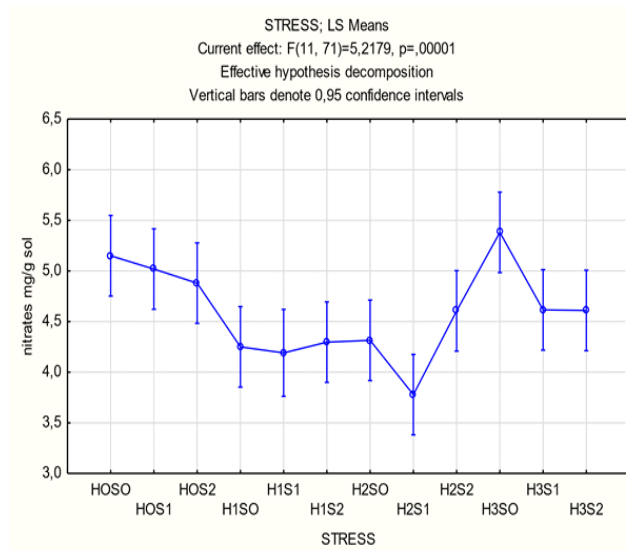


Figure 20: Effect of stress on the nitrate content in the soil .

With the interaction between stress and treatment, we see that treatment D1 records the highest values in relation to stress levels,

compared to treatments D2 and D0. The lowest nitrate content is observed with H2S2, at 4.60 mg/g of soil (Figure 21).

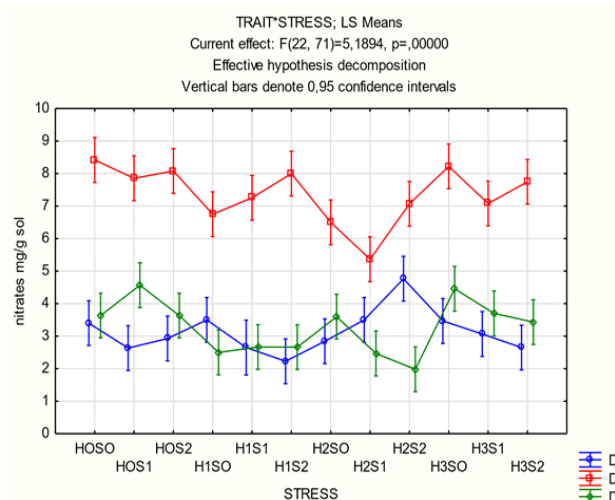


Figure 21: Effect of the stress * treatment interaction on the nitrate content in the soil .

2. Plant parameters

2.1. Chlorophyll A and B

The analysis of variance reveals a significant effect of treatment ($F=45.19$; $P<0.00001$), while the effect of stress is not significant ($F=1.46$; $P=0.165$). On the other

hand, the interaction between stress and treatment is significant ($F=2.11$; $P=0.009$). The highest values are obtained with dose D2 ($3.88\mu\text{g/g MF}$) and D1 ($3.48\mu\text{g/g MF}$), while the lowest value is noted with dose D0 ($1.99\mu\text{g/g MF}$) (Figure 22).

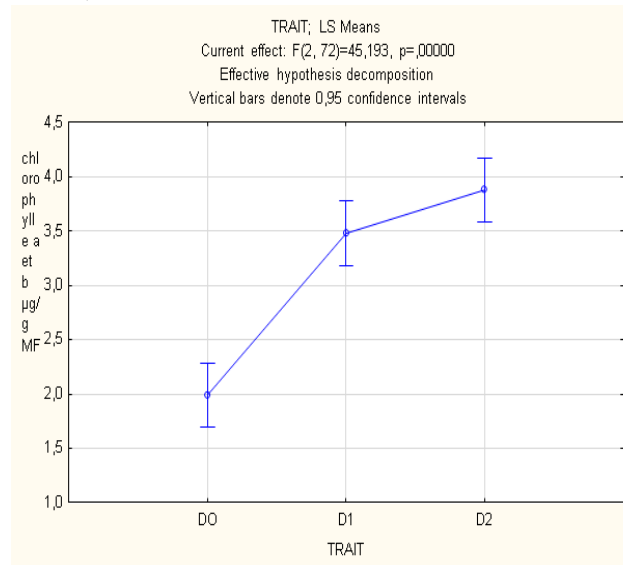


Figure 22: Effect of biochar treatment on the content of chlorophyll A and B.

The variation in chlorophyll a and b content is similar for all stress levels (Figure 23). Likewise, the interaction between stress

and treatment shows similar contents (Figure 24).

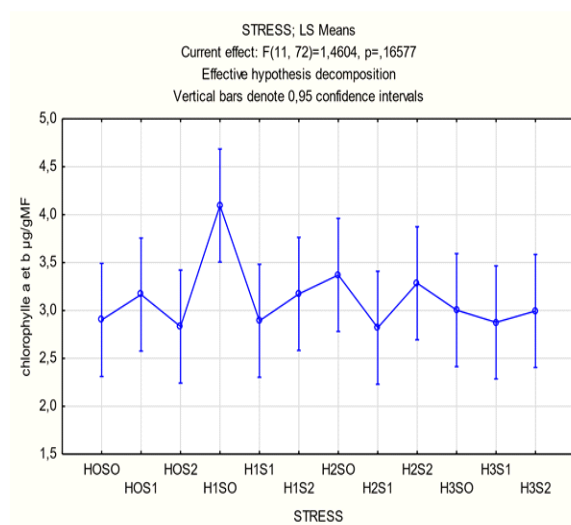


Figure 23: Effect of stress on the content of chlorophyll A and B.

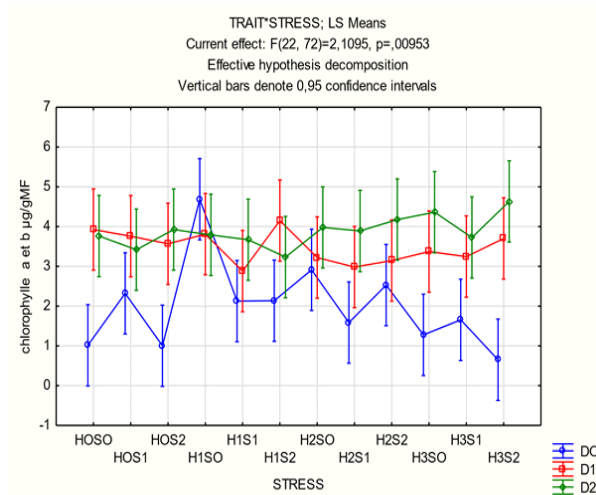


Figure 24: Effect of the stress*treatment interaction on the content of chlorophyll A and B.

4.2.7. Relative water content

The statistical analysis of the relative water content reveals a significant effect of the treatment ($F=31.57$; $P<0.00001$), as well as a significant effect of the stress applied to the plants ($F=19.22$; $P<0.00001$). In addition, the interaction between stress and treatment is also very significant ($F=4.34$; $P<0.00001$).

Biochar application resulted in an improvement in the relative water content of leaves. When comparing the means, three groups stand out, with the first group comprising D2 (45.54%) > D1 (44.00%) > DO (42.75%) (Figure 25).

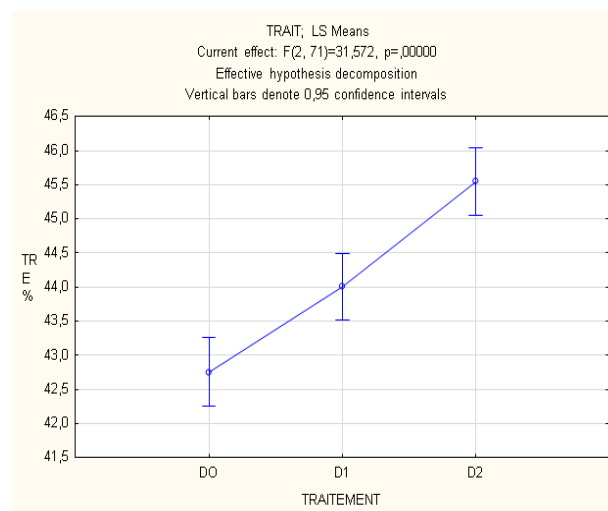


Figure 25: Effect of biochar on the relative water content of leaves.

The distribution of values under the effect of stress is divided into five distinct groups (Table 42; Appendix), with the highest

value of 47.93% observed at the HOSO level, while the lowest content is recorded at the H3S2 level (40.75 %) (Figure 26).

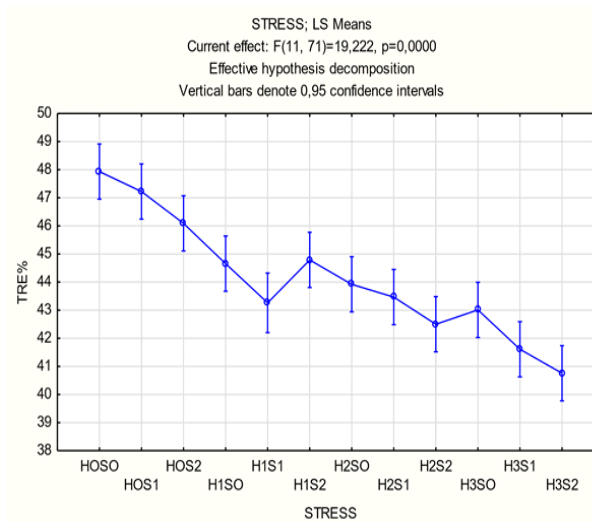


Figure 26: Effect of stress on the relative water content of leaves .

It is also notable that the D2 treatment induced a significant improvement in the relative water content of the leaves for all stress

levels, compared to the D1 and DO treatments (Figure 27).

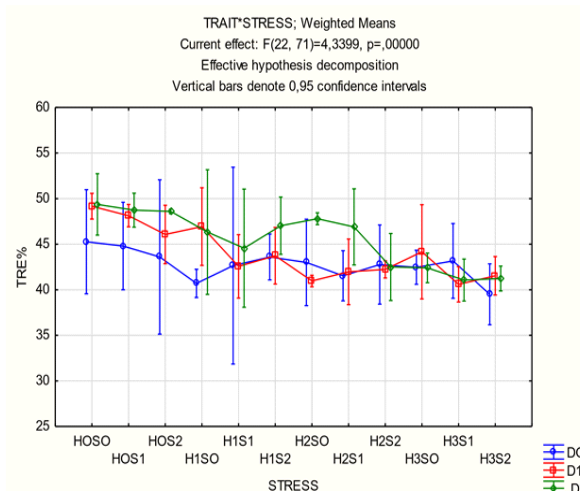


Figure 27: Effect of the stress*treatment interaction on the relative water content of the leaves.

3. Discussion

The addition of biochar has an alkalizing effect on soil pH, as observed in our study, this phenomenon being attributable to the composition of the bio-solid. Biochar characterization analyzes revealed its richness in active and total limestone, which, once

spread in the soil, leads to an increase in pH (Glaser et al., 1998). Furthermore, in the presence of stress, particularly water and saline stress, the soil pH tends to increase due to the accumulation of salts, while the alkaline ash present in the biochar also contributes to this alkalinity (ElNaggar et al., 2019).

Biochars produced by pyrolysis are generally alkaline, with pH increasing with production temperature. Although the addition of biochar increases soil pH, significant amounts can slightly reduce its alkalinity (Uzoma et al., 2011). This increase in pH can help combat soil acidification, particularly when biochar is incorporated into the soil (Lélé, 2016).

In our study, dose D1 of biochar showed better dilution of limestone in the soil, thus leading to a more significant increase in pH compared to dose D2. This observation can be explained by differences in soil moisture between pots D1 and D2, where increased humidity promotes better dissolution of limestone (Du et al., 2019; Sadoun, 2021).

The levels of active and total limestone increase in the soil under the effect of biochar amendment and applied stresses, confirming the role of biochar in improving the stock of these elements. However, the joint application of stress and biochar induced a decrease in the total limestone content compared to the control soil, suggesting a transformation of total limestone into active limestone. This transformation is favored by biochar, which activates enzymatic metabolism, unlike the control soil where enzymatic activity is negatively affected by stress (Du et al., 2019; Sadoun, 2021).

It is well established that sodium salts affect the physical and chemical properties of soil, inducing swelling and dispersion of clay elements, as well as a reduction in permeability, which can inhibit the mobilization of ions necessary for plants (David et al., 1999; Suarez et al., 2000; Shaggs et al., 2000). In our study, all pots that received biochar showed an increase in soil electrical conductivity, attributable to the presence of various organic and inorganic minerals in the biochar (Sadounet Messioughi, 2021).

The application of salt and water stress resulted in an increase in electrical conductivity,

especially with the highest stress levels. This increase can be explained by the role of the soil as a retention matrix for salts, which increases its osmotic potential and therefore electrical conductivity (ElOumri and Vieillefon, 1983). The addition of biochar, combined with water and salt stress, promoted an additional increase in electrical conductivity compared to the control soil, due to the release of mineral salts contained in the biochar (Chems, 2019).

Regarding soil moisture, the addition of biochar played a positive role in improving it, confirming its sponge effect to maintain water in the soil (Boudjabi et al., 2016). Although water content decreases with increasing stress levels, this decrease is attenuated when biochar is added, suggesting an interaction between biochar and stress, leading to enhanced water retention in the soil (Brodowski et al., 2006).

Biochar also had a positive effect on other soil properties, such as porosity, bulk density and water holding capacity, due to its stable and porous structure (Blanco-Canqui, 2017; Yanai et al., 2007). Furthermore, the interaction between biochar and organic matter improved soil structure by promoting the formation of stable microaggregates (Brodowski et al., 2006).

The addition of biochar also increased soil carbon content, consistent with its carbon-rich composition (Cornelissen et al., 2016). This increase in carbon content is important because it improves the soil's ability to adsorb nutrients and store water and carbon.

Regarding nitrates, their accumulation was observed mainly in the pots having received the D1 dose of biochar, while a decrease was observed with the D2 dose. This decrease can be attributed to strong adsorption of nitrogen by biochar, limiting its availability in the soil (Hugill, 2013). In addition, the joint increase in water and salt stress has led to a decrease in the mineralization of nitrogenous

organic matter, thus limiting the availability of nitrates in the soil (Boudjabi, 2016).

Regarding chlorophyll, the interaction between biochar and stress had a negative effect on total chlorophyll, which could be attributed to a reduction in the opening of leaf stomata to limit transpiration, leading to dilution chlorophyll (Dugo, 2002). However, an improvement in chlorophyll content was

observed with the addition of biochar, which can be attributed to its composition rich in essential elements for photosynthesis (Ouzounidou et al., 1992; Nandillon, 2019).

Finally, the relative water content of leaves was improved with increasing biochar treatments, which can be attributed to better water retention in the soil, thus preserving water available to plants (Boudjabi et al. , 2016).

CONCLUSIONS

The incorporation of biochar has demonstrated beneficial effects on soil properties and on several parameters associated with durum wheat plant growth. Biochar application played a significant role in mitigating the adverse effects of environmental stress on the plant and various soil characteristics, particularly by promoting the maintenance of adequate moisture levels.

However, it should be noted that at a higher dose of 60g per pot, imbalances were observed in nitrogen element levels. This finding highlights the importance of carefully considering biochar application rates to avoid any potential adverse effects.

REFERENCES

- DUGO, M.V.G. Effet du déficit hydrique sur l'état de nutrition azotée chez les graminées fourragères. Thèse Université de Poitiers. France. 189 p. 2002
- EL OUMRI, M., & VIEILLEFON, J. Étude expérimentale de la conductivité électrique globale des sols. Application à l'Estimation de Leur Salinité. Cah.ORSTOM, sér. Pédol, 10(2), 91-108. 1983
- EL-NAGGAR, A., LEE, S.S., RINKLEBE, J., FAROOQ, M., SONG, H., SARMAH, A.K., ZIMMERMAN, A.R., AHMAD, M., SHAHEEN, S.M. et OK, Y.S. Biochar application to low fertility soils: A review of current status, and future prospects. Geoderma337: 536-554 farmer-scale charcoal/biochar production. PLoS ONE, 11(5), 1-16. 2019
- GLASER B., HAUMAIER L., GUGGENBERGER G., ZECH W. Black Carbon in Soil: the use of benzenecarboxylic acids as specific markers. OrganicGeochemistry, 29: 811-819. 1998
- GRABER, E.R., HAREL, Y.M., KOLTON, M., CYTRYN, E., SILBER, A., DAVID, D.R., TSECHANSKY, L., BORENSHTEIN, M., ELAD, Y. Biochar impact on development and productivity of pepper and tomato grown in fertigated soilless media. Plant and Soil 337, 481–496. 2010
- GUO, M. The 3R Principles for Applying Biochar to Improve Soil Health. SoiSyst., 4(1), 9. 2020

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- HUGILL, B. Le Biochar-Une maison biologique pour les microbes du sol. 17391 Durrance Road, North Fort Myers, Florida 33917, USA | 239.543.3246. 2013
 - LEHMANN J, RILLIG MC, THIES J, MASIELLO CA, HOCKADAY WC, CROWLEY D. Biochar effects on soil biota – A review. *Soil Biology and Biochemistry*, 43, 1812– 1836. 2011
 - LÉLÉ, N.B. Potentiel d'amélioration de la fertilité des sols sableux et acides de Kinshasa (RDC) par l'usage du charbon des bois (biochar), de la biomasse végétale et des engrais minéraux. Thèse de doctorat. Université de Liège, Belgique, 196. 2016
 - LIU, S., ZHANG, Y., ZONG, Y., HU, Z., WU, S., ZHOU, J., JIN, Y., ZOU, J. Response of soil carbon dioxide fluxes, soil organic carbon and microbial biomass carbon to biochar amendment: a meta-analysis. *GCB Bioenergy* 8, 392–406. 2016
 - MANYA, J.J. Pyrolysis for biochar purposes: A review to est ablish current knowledge gaps and research needs. *Environmental Science and Technology* 46, 7939–7954. 2012
 - NANDILLON, R. Phytostabilisation des éléments métalliques d'un technosol minier végétalisé par le genre *Salix* assistée par du Biochar (Doctoral dissertation, Université d'Orléans). 2019
 - PILETLAIN, F., MATHIEU C. Analyse chimique des sols. Méthodes choisies. Lavoisier édition TEC et DOC. 376p. 2003
 - REVELL, K.T., MAGUIRE, R.O., AGBLEVOR, F.A. Influence of poultry litter biochar on soil properties and plant growth. *Soil Science* 177, 402–408. 2012
 - RODIER, J., BAZIN C., BROUTIN J. C., CHAMBON P., CHAMPSAUR H., RODI L. 1996
 - SADOUN, A., & MESSIOUGH, M. Etude du pouvoir tampon (équilibre pH) d'un sol sablonneux traité avec un bio-charbon d'origine végétale dans la région d'El-Oued. 2021
 - SAIDI, D., LE BISSONNAIS, Y., DUVAL, O., DAOUD, Y., & HALITIM, A. Effet du sodium échangeable et de la concentration saline sur les propriétés physiques des sols de la plaine du Cheliff (Algérie). *Etude et gestion des sols*, 11(2), 137-148. 2004
 - WATTS, C.W., WHALLEY, W.R., BROOKES, P.C., DEVONSHIRE, B.J., WHITMORE, A.P. Biological and physical processes that mediate micro-aggregation of clays. *Soil Science* 170, 573–583. 2005
 - YANAI, Y., TOYOTA, K. et OKAZAKI, M. Effects of charcoal addition on N₂O emissions from soil resulting from rewetting air-dried soil in short-term laboratory experiments. *Soil Science and Plant Nutrition*, 53, p : 181-188. 2007.