The Effect of Biochar, Wheat Residues, Saline and Non-Saline Soils on CO_2 Emissions and specific Chemical characteristics of soil

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Abstract

One of the serious challenges facing soil scientists is soil salinity, degradation, and productivity preservation, which directly impacts agricultural production and food security. This study aims to evaluate the effect of plant residues (wheat straw, and biochar derived from wheat straw) on two different soils (saline and non-saline) on specific parameters (organic matter, EC, CEC, and pH), and the amount of CO_2 released.

A 60-day laboratory incubation experiment was carried out to evaluate the organic matter content, pH, cation exchange capacity (CEC), and electrical conductivity (EC), and released CO_2 by the application of wheat residues (Symbolized as w), biochar (Symbolized as b), compared to the control treatment (Symbolized as c), under a completely randomized design (CRD) with three replicates. Results revealed that the total amount of CO_2 released recorded the most significant values released among the treatments, As the wheat residues recorded the highest values followed by Biochar, and control treatments in both soils. Also the Non-saline soil recoded the highest values of Co2 (74.02 mg CO_2 /100 g soil/day) compared to the saline soil (51.2 mg CO_2 /100 g soil/day). Also the CEC values recorded the highest values under the interaction of saline soil and wheat residues, and biochar reached 14.39 and 15.28 cmol·kg^{-1} respectively, compared to the non-saline treatments which were recorded were 13.91 and 11.05 cmol·kg^{-1}, respectively, considering the both treatments were higher than the control treatment.

Keywords: Wheat residues, Carbon dioxide (CO_2), Saline soils, Organic materials.

Introduction

Soil considered as a habitat for uncountable organisms, including plants, animals, humans, and microorganisms. Moreover, it is one of the major factors of agricultural production, Which is vital resource for feeding the world's growing population [50]. Therefore, improving soil properties represents a significant challenge around the world, despite intensive efforts aimed to mitigate the factors that degrade soil quality and loose sustainability.

Soil salinity is a major challenge facing the land productivity. it has been reported in centuries, with human societies historically coexisting with saline conditions. Today, soil salinity remains a critical global concern due to its detrimental impact on agricultural productivity, long-term soil sustainability, and the reduction of arable land. Salinity-related problems occur across all climatic zones and may arise from both natural processes and anthropogenic activities. Saline soils are particularly widespread in arid and semi-arid regions, where rainfall is limited to meet crop water demands. Under such conditions, plants experience **water stress** due to high salinity levels, elevated evapotranspiration rates, and limited water availability in the rhizosphere [37]. High salinity affects directly the vegetative and reproductive growth, and significantly inhibit photosynthesis, carbon assimilation, and nitrogen metabolism [46]. This results in physiological drought symptoms, including leaf desiccation, reduced chlorophyll content, and diminished photosynthetic efficiency [34].

The application of plant-based organic residues is considered one of the most effective approaches for salinity mitigation, and soil enhancement. These treatments contribute to improve root growth and more efficient utilization of water and nutrients. Additionally, regulating the plants water absorption and increase leaf water content, which positively influences vegetative growth. Organic residues also contribute to soil warming during cold seasons, especially in winter, by increasing the temperature around the root zone, thereby stimulating root development and enhancing nutrient absorption. Moreover, to retain moisture in light-textured soils and reduce water content in heavy soils, minimize erosion caused by wind and water, and stimulate microbial activity in the soil [5]. The application plant residues on the soil can decrease the drought stress and salinity by enhancing the soil porosity, which promotes water infiltration and percolation of salts beyond the root zone, particularly in well-reclaimed soils. This practice also reduces the incidence of soilborne diseases and minimizes the need for chemical fertilizers, while simultaneously increasing the availability of most macro- and micronutrients in the soil [16]. Furthermore, mixing organic plant residues with soil has been shown to enhance microbial diversity and distribution, activate soil enzymes, and significantly improve nutrient uptake by plants [47,58].

Plant residues have been widely utilized by farmers, either by the direct application on the soil as fresh organic matter or pyrolyzed into biochar. These agricultural practices aim to preserve soil organic matter and sustain microbial activity by applying biofertilizers or integrating wheat residues into the soil through burial [44]. Biochar, often referred to as "black gold," is produced through the pyrolysis of organic biomass such as crop residues at high temperatures under limited oxygen conditions. This thermal decomposition leads to a stable product with reduced environmental impact [39,42]. Numerous studies have demonstrated that biochar possesses a high specific surface area, a substantial charge density [45], low bulk density [27], stable porous structure, and elevated organic carbon content [24]. These characteristics can reduce soil bulk density and enhance water retention in coarse-textured soils due to biochar's large surface area [56]. Moreover, biochar can positively influence the chemical and biological properties of soil, including pH [2], and cation exchange capacity (CEC) [31]. The amount of carbon dioxide (CO_2) released from organic residues is commonly used as an indicator to assess the degree of organic matter decomposition and to monitor enzymatic activity of soil microorganisms [10]. Among the available methods, this is one of the most widely adopted [33]. The application of organic residues is a well-established agricultural practice, often used in conjunction with tillage operations, wherein crop residues were applied to the soil surface to prevent erosion, reduce moisture loss, and enhance nutrient cycling [53].

These residues, such as wheat residues, whether applied on the soil surface or incorporated through tillage, can influence mineralization processes and CO_2 emission due to their significant effect on soil temperature during such processes [20,35]. The decomposition of plant residues in soil leads to carbon mineralization by microorganisms, which forms the microbial secondary metabolites and the accumulation of stable organic compounds [54]. This process is accompanied by the release of carbon dioxide (CO_2), thereby returning a portion of the carbon to the atmosphere [26]. Soil microbial activity and the decomposition processes that transform plant-derived carbon into soil organic matter (SOM) and CO_2 are significantly influenced by environmental soil properties [20,25]. Numerous studies have reported that CO_2 is the most abundant greenhouse gas emitted from soils, with a flux rate over one hundred times greater than that of N_2O and CH_4 [1,12,48].

One of the most serious challenges in soil science is the increase in soil salinization and its associated degradation, which directly affects agricultural productivity and food security. soil preservation and sustaining the production capacity require serious strategies and practices that maintain the soil chemical and physical properties over time. In this context, the present study aims to evaluate the effects of plant residues (wheat straw) and biochar derived from wheat straw into two soil types (saline and non-saline) on specific chemical characteristics of the soil (organic matter content, electrical conductivity (EC), cation exchange capacity (CEC), and pH), as well as on biological activity through the quantification of CO_2 emissions.

Materials and Methods:

Two soil samples were collected on depth of (0–30 cm) in Diyala Governorate, Iraq, one sample was saline and the other non-saline, as shown in Table 1. The samples were air-dried and passed through a 2 mm sieve. The soil samples were stored in plastic containers and subjected to chemical and physical analyses.

Table (1): Location and coordinates of soil samples used in the study

Coordinates	Location	sample
N "396. 51'42°33 E "35.482'34°44	The University of Diyala fields	Saline soils
N "06.143'41°33 E 090. 46' 34°44"	The University of Diyala fields	Non-saline soils

Two laboratory experiments were carried out. The first was an incubation experiment for 60 days, aimed to evaluate specific chemical characteristics of the soil which were organic matter content, pH, cation exchange capacity (CEC), and electrical conductivity (EC), under the application of wheat residues (Symbolized as *w*), biochar (Symbolized as *b*), and a control treatment (Symbolized as *c*) and according to the Completely Randomized Design (CRD) with three replicates per treatment. The second experiment was a factorial study to evaluate the carbon dioxide (CO_2) released from the soil, consisted of three treatments: soil salinity (saline and non-saline), organic matter (as in the first experiment), and incubation duration. This experiment also followed a Completely Randomized Design (CRD) with three replicates for each experimental unit.

Chemical and Physical Properties

The following soil characteristics were determined as described by Al-Tamimi [7]:

1. **Electrical Conductivity (EC) and pH**
   EC and pH were measured in a 1:1 soil-to-water extract.
2. **Available Potassium and Sodium**
   Extracted using ammonium acetate and determined using a Flame Photometer.
3. **Soluble Cations and Anions**
   - Calcium (Ca^{2+}) was measured by titration with 0.01 N versenate.
   - Magnesium (Mg^{2+}) was measured using an Atomic Absorption Spectrophotometer.
   - Sodium (Na^{+}) and Potassium (K^{+}) were measured using a Flame Photometer.
   - Carbonates (CO_3^{2-}) and bicarbonates (HCO_3^{-}) were determined by titration with 0.01 N sulfuric acid.
   - Chloride (Cl^{-}) was determined by titration with 0.005 N silver nitrate.
   - Sulfates (SO_4^{2-}) were titrated using 0.2 N versenate.
4. **Cation Exchange Capacity (CEC)**
   CEC was measured using the Bower method. By saturation with 1 N sodium acetate, wash with alcohol to remove excess acetate, and the adsorbed sodium was displaced with 1 N ammonium acetate.
5. **Organic Matter (OM)**
   Determined by the modified Walkley-Black wet oxidation method.

Table (2): Some physical and chemical characteristics of the two study soils before treatment with biochar

Non-saline	Saline	characteristics
8.68	8.16	pH
3.18	9.11	EC ds m^{-1}
57.32	79.8	K mg kg^{-1}
755.44	1167.07	Na mg kg^{-1}
128	920	Ca mg kg^{-1}
302.56	1268.8	Mg mg kg^{-1}
539	1862	Cl mg kg^{-1}
1398.28	2917.53	SO_4 mg kg^{-1}
300	280	HCO_3 mg kg^{-1}

Biochar Preparation

Biochar was entirely produced from wheat residues at a temperature of 300 °C using an electric oven (Napentem-Germany) for two hours, with a heating rate of 61 °C min^{-1} under limited oxygen conditions. The produced biochar was brought to the laboratory and passed through a 50 µm sieve as recommended by Fahmi et al. [19]. The biochar samples were stored at room temperature. Table (3) presents some of the physical and chemical characteristics of the biochar.

Determination of Selected Physical and Chemical Properties of Biochar

pH Measurement

A 4 g sample of biochar was weighed and transferred into a 250 mL glass flask. Then, 100 mL of distilled water was added, and the flask was covered with a glass cover. The mixture was heated for 5 minutes after boiling. The supernatant was decanted at 60 °C, allowed to cool to room temperature, and the pH was measured using a Savova pH meter.

Electrical Conductivity (EC)

A 1% (w/v) biochar suspension was prepared using distilled water and shaken for 24 hours. The supernatant was poured, and the electrical conductivity was measured using a Suliman EC meter [51].

Cation Exchange Capacity (CEC)

The cation exchange capacity was measured following the method of Gillman and Sumpter [22]. One gram of biochar was placed in a test tube, and 20 mL of 0.5 N barium chloride ($BaCl_2$) solution was added. The mixture was centrifuged at 200 rpm for two hours. The supernatant was filtered through filter paper with a 0.42 µm pore size. The concentrations of exchangeable cations (K^+, Ca^{2+}, Mg^{2+}, Na^+, Fe^{2+}, and Mn^{2+}) were determined in the filtrate, and the cation exchange capacity was calculated by summing their values.

Table (3): Some chemical properties of biochar

Wheat residues	Biochar	Unit	characteristics
8.02	7.55	------------	pH
5.61	6.11	(ds m^{-1})	EC
62.94	61.44	($Cmol_c$ kg^{-1})	CEC

Estimation of Released Carbon Dioxide (CO_2)

A 250 g sample of each soil type (saline and non-saline) was taken, and two types of organic materials were added (biochar and wheat residues), in addition to a control treatment. The treatments were thoroughly mixed with the soils at an application rate of 2% (w/w), with three replicates per treatment. The mixtures were placed into airtight glass jars, and distilled water was added to adjust the moisture content to 70% of field capacity. Moisture loss was recovered by weighing the jars and distilled water as required to maintain the desired moisture. The samples were incubated at 30 ± 2 °C for 60 days.

CO_2 emissions from the soil were measured at the following intervals:

1. Daily from day 1to day 3.
2. Weekly from day 4 to day 60.

The quantity of released CO_2 was determined using the method of Janzen (1987), according to the following formula:

CO_2/100g Soil=(B−V)×N×E

Where:

- **B** = Volume of acid consumed (mL) in the blank
- **V** = Volume of acid consumed (mL) in the treatment
- **N** = Normality of HCl
- **E** = Equivalent weight of CO_2 = 22

15 mL of 1 N sodium hydroxide (NaOH) was poured inside airtight jars. After incubation, the residual NaOH was titrated with hydrochloric acid (HCl). CO_2 reacts with NaOH to form turbid sodium carbonate (Na_2CO_3), which is precipitated by the addition of barium chloride ($BaCl_2$) solution (50%). The titration was conducted using 0.5 N HCl, with phenolphthalein as an indicator to determine the endpoint. The following reactions occur:

$2NaOH+CO_2 \rightarrow Na_2CO_3+H_2O$ (turbid solution)

$Na_2CO_3+BaCl_2 \rightarrow 2NaCl+BaCO_3$ (white precipitate)

Statistical Analysis

Data were gathered and analyzed using Analysis of Variance (ANOVA) according to a Completely Randomized Design (CRD). Treatment means were compared using Duncan's multiple range test at the 0.05 significance level. All statistical analyses were performed using SAS version 9.4.

Results and Discussion

Carbon Dioxide (CO_2) Emissions

Figures 1 and 2 shows the amount of carbon dioxide (CO_2) emitted from saline and non-saline soil samples treated with two types of organic factors (biochar and wheat residues) compared to the control treatment over a 60-day incubation period. The emission curves shows three distinct phases of CO_2 release across the treatments, representing three temporal phases. The first phase, (1–10 days of incubation), is characterized by a sharp increase in CO_2 emission, particularly in non-saline soils. This initial peak can be attributed to the increment of microbial activity, as the microorganisms rapidly resumed their biological functions and commenced decomposition of readily biodegradable substrates such as simple sugars and carbohydrates derived from the applied organic matters [8,13,36]. The second phase, extending from day 10 to 42, shows a decline in microbial activity, largely due to the depletion of easily decomposable compounds. During this period, more non-biodegradable organics such as cellulose, hemicellulose, and lignin, known with complex chemical structures and resistance to microbial degradation [30,43]. The third phase, from day 42 to 60, shows an increase in CO_2 emissions, likely resulting from the microbial decomposition of dead microbial biomass by the living microorganisms. Additionally, the breakdown of previously resistant compounds such as cellulose, hemicellulose, and lignin was facilitated by prolonged enzymatic activity, which leads to make it accessible and biodegradable, which contributed to the CO_2 emissions observed at the beginning of this phase. Overall, the total CO_2 emissions from both saline and non-saline soils were higher in the treatments of biochar and wheat residues compared to the control. These results were in agreement with previous studies conducted by Saeed and Al-Saadi [49], Al-Obaidi and Mohammed [6], Walpola and Arankumara [58], Al-Amery [4], Fahmi [18], and Fadil and Fahmi [17].

Table 4 reveals statistical significance in the values of total CO_2 emissions (mg CO_2 /100 g soil/day) among the different treatments. For both soil types, the treatments ranked as following in terms of CO_2 emissions, wheat residues > biochar > control. Significant differences were also observed between the saline and non-saline soils under the control treatment, with emission rates of 74.02 and 51.2 mg CO_2 /100 g soil/day for the non-saline and saline soils, respectively. The wheat residue treatment shows the highest CO_2 emissions, followed by biochar, with average rates of 181.57 and 167.01 mg CO_2 /100 g soil/day for the non-saline and saline soils, respectively. Also, total CO_2 emissions over the entire incubation period were higher in non-saline soils compared to saline soils, with cumulative values of 2178.94 and 2004.15 mg CO_2 /100 g soil/day, respectively.

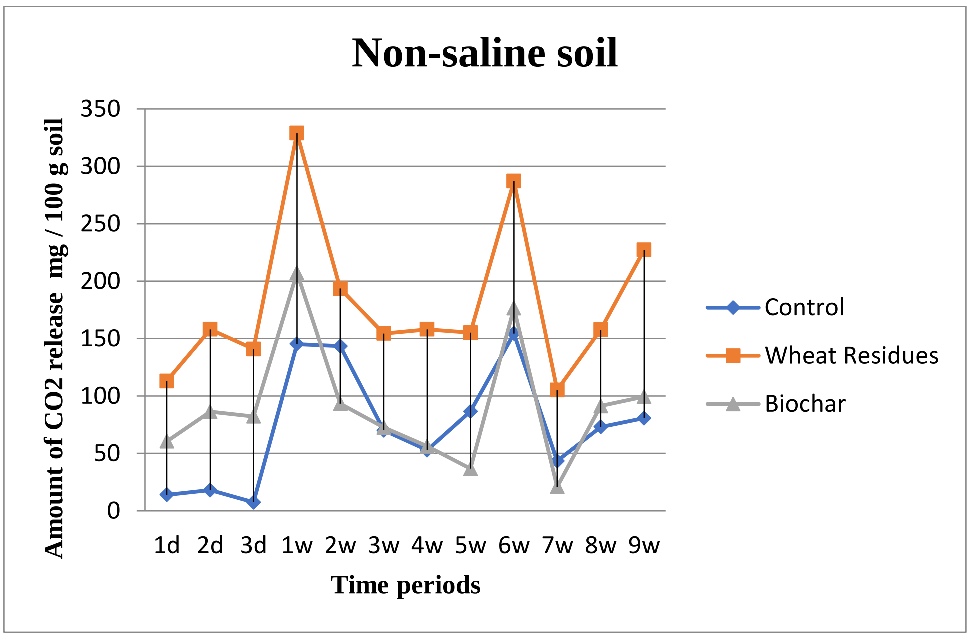

Figure (1): Chart showing the amount of released CO_2 gas in non-saline soil

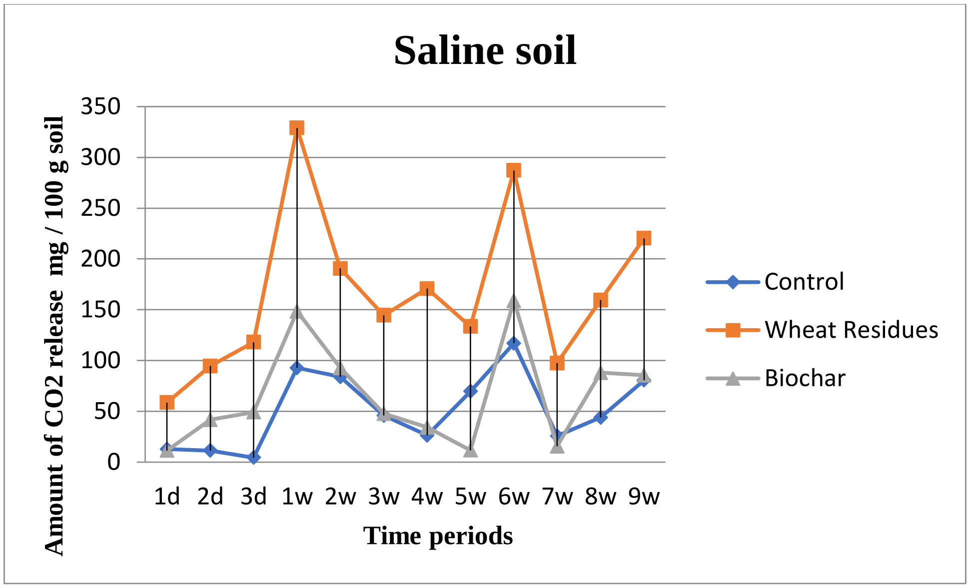

Figure (2): Chart showing the amount of released CO_2 gas in saline soils

Table (4): Amount of released CO_2 gas in saline and non-saline soils (mg CO_2/100 gm soil/day)

Moral difference	Value	Treatment
A	2178.97	Non-saline soil + Wheat residues
B	2004.2	Saline soil + Wheat residues
C	1206.33	Non-saline soil + Biochar
E	901.63	Saline soil Biochar
E	888.37	Non-saline soil + Control
G	614.57	Saline soil + Control

Chemical characteristics

The results in Table 5 indicates that the pH values in the studied soil samples ranged between 7.70 and 8.37 in both saline and non-saline soils. Which indicates that the application of biochar in both soil types reduces the pH values to approximately 7.70–7.74, compared to the treatments with wheat residues and the control. This result is due to the increase in soil organic matter and the decomposition processes [55], in addition to the presence of cationic compounds within the biochar. Moreover, electrical conductivity (EC) in the saline soil sample treated with biochar showed a significant increase compared to the other treatments, reaching a maximum value of 9.40 $dS \cdot m^{-1}$. These results were in agreement with previous studies by Fadil and Fahmi [17], Zhang et al. [59], Bayu et al. [9], and Van Zwieten et al. (56), which noted that biochar application reduces soil pH while progressively increasing EC due to its high content of exchangeable cations such as K^+ and Na^+, as revealed in Table 3. Which were noted by, DeLuca et al. [14], that biochar application can regulate electrical conductivity.

Results in Table 2 shows that the cation exchange capacity (CEC) increased in saline soils under the wheat residues and biochar treatments, reaching 14.39 and 15.28 $cmol \cdot kg^{-1}$, respectively, compared to the non-saline soils, which were recorded 13.91 and 11.05 $cmol \cdot kg^{-1}$, respectively, compared to control treatment which revealed the lowest values. This increase can be attributed to the characteristics of the biochar's feedstock, particularly its variable surface charges and high specific surface area, which enhance the soil's CEC, those results were agreed by Suliman et al. [51]. Results in Table 5 also shows an increase in exchangeable sodium (Na^+) and potassium (K^+) ions in both soil types due to biochar application compared to other treatments. This significant increase in exchangeable cations in biochar-treated soils can be due to the ash content of the biochar, which facilitates the immediate release of adsorbed mineral nutrients [40]. These results are consistent with Geng et al. [21].

The results further revealed an increase in soil organic matter content in both saline and non-saline soils due to biochar treatments, with values reaching 5.85% and 5.36%, respectively. The application of biochar improved several chemical characteristics of the soil, particularly organic matter content. significantly, biochar application has increased the average CO_2 emissions, indicating enhanced microbial activity in the soil. The observed increase in organic carbon (OC) is a result of the increase in organic biomass due to the biochar application [32,55]. Hafeez et al. [23] and Dume et al. [15] also confirmed that biochar application increased organic matter and organic carbon levels, though the degree of increase varies among different soil types. The variability in soil organic matter content is mainly due to differences in nitrogen content and the N:C ratio, as well as variations in gypsum content, which can influence the rate of organic matter decomposition [4]. Also, gypsum dissolution can lead to the formation of coatings and chemical complexes around organic matter, thereby inhibiting the activity of decomposition organisms and their enzymes, ultimately increasing organic matter content [52].

Table (5): Some chemical properties and cation exchange capacity for saline and non-saline soil samples treated with biochar and wheat straw.

O.M	Na^+	K^+	CEC	EC	pH	Treatment	Soil type
2.75	66.46	19.04	13.26	8.35	8.00	c	Saline
4.36	76.99	26.99	14.39	8.18	8.22	w	Saline
5.85	79.78	49.91	15.28	9.40	7.70	b	Saline
3.44	35.47	22.66	9.50	3.47	8.27	c	Non-saline
4.56	41.52	31.92	13.91	4.38	8.37	w	Non-saline
5.36	53.02	58.15	11.05	6.05	7.74	b	Non-saline

Conclusion

The application of wheat residues and biochar derived from wheat residues to both saline and non-saline soils has increased the CO_2 emissions compared to the control treatments, considering that the wheat residue treatments recorded more significant values compared to biochar in terms of CO_2 release. Also, to the improvement of the chemical characteristics of the soils. Therefore, this study recommends the application of organic residues in the form of biochar, as its slower decomposition rate ensures prolonged positive effects on soil quality over time.

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