Original Article

Evaluation of chemical changes of plant residues in biochar and its effects on microbial respiration of two acidic and calcareous soils

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Abstract

Biochar is a carbon-rich solid produced via the thermal decomposition of plant biomass under anoxic conditions. It can be used as a modifier to improve soil chemical properties in soils with poor soil conditions and to enhance soil fertility through increasing soil organic carbon storage. On the other hand, biochar is a long-term mechanism for carbon sequestration in poor organic matter soils. It can affect soil chemical properties such as cation exchange capacity (CEC), acidity and nutrient concentration. The effect of three types of biochar prepared from beech residues, rice bran and pistachio shell on soil chemical properties were evaluated in this study. The biochars were obtained by heating various plant residues at 400 °C for 120 min under low oxygen conditions. Chemical decomposition results revealed that carbon and phosphorus concentrations increased as a result of conversion of plant residues to biochar, but nitrogen and hydrogen concentrations decreased. The results also showed that biochar has a significant effect on soil microbial respiration.

Keywords: Organic matter, biochar, carbon sequestration.

INTRODUCTION

Several scientists believe that soil organic matter is the soil quality indicator assessment because it is strongly linked to soil physical, chemical and biological properties [1]. The organic carbon level stored in soil results from two important biological processes that produce organic matter on the one hand and decompose organic matter on the other side. These two processes have strong physical and biological controllers, the most important of which are climatic conditions, soil physico-chemical and biological features, chemical composition and type of plant residues, inaccessibility of organic matter to soil organisms, agronomic management, and the interaction of these factors with each other [2].

Allison (1973) indicated the beneficial role of soil organic matter as follows: (1) Organic matter is a source of minerals and energy for plants and soil organisms, (2) Organic matter retains nutrients by chelating them in the soil, (3) Organic matter enhances aggregation and root development, (4) Organic matter improves water penetration into the soil and increases water use efficiency (WUE), and (5) Organic matter improves soil physical properties and facilitates agricultural operations. Accordingly, organic matter has received increasing attention in recent decades due to its beneficial effects on crop production.

Soil organic matter is composed of all plant, animal and microbial residues in various stages of decay. Soil organic matter or carbon content in soil is an indicator of sustainable agriculture and plays a critical role in sustainable production as well as prevents soil degradation [3] . Multiple studies have been conducted on the effect of organic matter on improving physicochemical properties of soils. Soil organic carbon (SOC) significantly affects the quality and various aspects of soil, one of which is the sequestration of carbon and nitrogen compounds [4] .

Soil organic matter consists of two active and passive parts. Active soil carbon reserves as sensitive indicators have been suggested to observe changes in soil organic matter [5]

Soil organic matter is a natural, important source of nutrients for crops and orchards. Harvesting crop residues from agricultural fields reduces soil fertility because plant residues are a source of macro-nutrients (e.g., nitrogen, potassium, and

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phosphorus) and micro-nutrients (e.g., zinc, iron, manganese, etc.). On the other hand, crop residue harvesting increases runoff and erosion rates and accelerates mineralization of soil organic carbon due to changes in temperature and humidity in non-vegetated soils. All of these factors will lead to nutrient loss. Lveland and Webb (2003) indicated that depletion of soil organic carbon resulted in reduced nutrient release in soil and reduced nitrogen storage.

Baldock and Nelson (1999) defined soil reversibility as the capacity of the ecosystem to return to its original state after degradation; in other words, the reversibility feature is one of the soil properties that determines how a system can repair itself. Nannipieri et al. (2003) indicated that soils with higher microbial diversity are more resistant than soils and have more reversible properties than soils with less microbial diversity. Soil organic carbon content, cation exchange capacity (CEC) and microbiota were higher in rangeland soils and showed that these factors increased the resistance of soil microorganisms to environmental stresses. Soil reversibility is actually a measure of the whole soil system controlled by physical, biological and chemical factors, in which the amount of soil organic matter and chemical composition play a key role.

Oades et al. (1989) reported that soil CEC decreased with soil depth and soil organic matter depletion, although no change in soil composition and clay content was observed. One percent increase in soil organic carbon content resulted in one unit increase in CEC of variable load soils.

Plant biomass yields that require more carbon utilization in the photosynthesis process are enhanced by the use of biochar. Soil nutrition depletion associated with food insecurity, global warming and the urgent need for renewable energy are among the growing global challenges. Biochar production technology has been suggested as a viable solution to these challenges [6] .

Biochar is produced by incomplete combustion of plant biomass or unusual agricultural waste [7]. Furthermore, biochar and its by-products (synthetic gases and bio-oils) can be produced from a wide variety of materials such as organic waste and wood with a high lignin to cellulose ratio. In fact, thermal decomposition of organic matter under low temperature creates a charcoal-like material – called biochar – that has a high capacity to absorb nutrients. Most carbon of biochar is aromatic, which is resistant to decomposition when added to soil [8] . Biochar has different nutrient content as produced from variety of plant biomass residues and under different conditions of thermal decomposition. For instance, total nitrogen and phosphorus of biochar from animal manure residues are higher than the concentration of these elements in biochar obtained from plant biomass [9] .

Various processes can be used to convert energy stored in biomass into useful energy. The selection of process type depends on factors such as biomass type, biomass value, environmental standards and economic conditions [10] .
Saxena et al. (2008) suggested thermal processes and biochemical and biological processes to convert energy stored in biomass into useful and usable energies, which can be classified into primary and secondary processes.

Biochar can well control the quality of the environment due to controlling the spread of contaminants and managing organic waste [11] . Converting agricultural waste to biochar saves the cost of these wastes [12] . Agricultural wastes have many agricultural benefits due to their ability to provide the nutrients needed by plants such as carbon, nitrogen, potassium, phosphorus, calcium and magnesium, and if these wastes are used for biochar production, overuse of chemical fertilizers can be avoided [13] .

Steiner et al. (2008) confirmed that biochar acts as an adsorbent, thereby reducing nitrogen leaching and increasing nitrogen efficiency. Nitrogen efficiency is crucial in the future in terms of maintaining population growth.
Addition of biochar to the soil slows down the rate of nitrogen mineralization compared to the addition of raw biomass to the soil [14] . Likewise, addition of biochar to the soil may reduce net nitrogen mineralization or increase net mineralization [15] .
Knowledge on the physicochemical properties of biochar is essential to understanding how biochar plays a role in a particular soil type.

The present study aims to understand how thermal decomposition process conditions and plant biomass properties affect the biochar characteristics, and what the effect can be observed on the soil microbial properties when biochar is used as a soil modifier.

Method

Three types of biochar were produced using rice bran, beech residue and pistachio shell in order to study the effect of biochar on the properties of two acidic and calcareous soils. Rice bran and beech residue were obtained from the northern regions of Iran and pistachio shells were provided from the southern regions of Iran. The studied acidic soils were obtained from the north of the country and the used calcareous soils were provided from Zanjan city. The crop residues were first cut into small pieces using a Slicer/Shredder machine. The fragments were incubated and dried in the oven for 72 h at 50-60 °C. Crop residue was then poured into special boxes where air oxygen could not penetrate and placed in an electric oven set at 400–450 °C for 2 h. Biochars were crushed in mortar after preparing and then passed through a 0.5 mm sieve and mixed with 3 kg of acidic and calcareous soils at 2% and 4% ratios and the soils. Cows were seeded in pots at 25 °C for 3 months under moisture conditions. After three months, the pots were sampled and the physicochemical properties of the soils were measured.

Determination of the soil biological properties

Soil Microbial Respiration: Soil respiration is defined as the uptake of oxygen by soil microorganisms and involves the exchange of gas through aerobic metabolism (Page, 1986). In this study, microbial respiration (carbon mineralization) in soil (30 samples) was measured daily for 6 months in the first week and then once a week. During the study, the soil-free sample was treated as a control with the same conditions to deduct carbon dioxide absorbed from the laboratory or testing respiration from total emitted carbon dioxide and to measure actual carbon dioxide. The difference in the volume of acid used for titration of the control sample and the soil sample was calculate, and the result was placed in the following equation to obtain the amount of carbon dioxide produced in the soil.

$$Ct=\frac{(B-S).N.E.1000}{W} \quad (1)$$

Where C_t is the value of carbon emitted by microbial respiration in mg kg^{-1}, B is the volume of acid consumed for control (ml), S is the volume of acid consumed for sample (ml), N is normality of used acid, E is the Equivalent weight to carbon, W is the oven-dried weight of soil (g) and 1000 is the conversion factor of soil from g to kg.

Measurement of chemical properties of plant residues and biochar

- Carbon content of plant residues and their biochars was determined by CHNO analyzer and reported as carbon percentages of plant residues and their biochars.
- Nitrogen content of plant residues and their biochars was determined by CHNO analyzer and was reported as nitrogen percentage of plant residues and their biochars.
- Phosphorus content of plant residues and their biochars was determined by Kummer technique and was reported as phosphorus percentage of plant residues and biochar.

The experiment was conducted in a randomized design with seven treatments and three replications. Statistical analysis of data was performed using statistical software of SAS and means were compared by Duncan's multiple range test.

Results and Discussion

Evaluation of chemical changes of plant residues during conversion to biochar

Biochar carbon concentration

The results of means comparison by t-test showed that there was a significant difference between the carbon concentration of the primary plant residues and their biochar at 1% probability level (Table 1) and their carbon concentration increased during the conversion of plant residues to biochar. Carbon concentration increased during the conversion of rice bran, beech residues and pistachio shell to biochar by 24.5%, 64.2% and 55.7%, respectively.

Biochar nitrogen concentration

The results of comparison of means by t-test showed that there was a significant difference at 1% probability level between nitrogen concentration of raw residues and their biochar (Table 1). During the conversion of plant residues to biochar, their nitrogen concentration decreased, so that it declined during the conversion of rice bran, beech residues and pistachio shell to biochar by 16.2, 22.24 and 20%, respectively. Entire raw plant residues lost about half their nitrogen during the thermal decomposition process at 400 °C due to nitrogen being released into the gas [16] .

Biochar phosphorus concentration

The results of comparison of means by t-test showed that there was a significant difference between phosphorus concentration of plant residues and their biochar at 1% probability level (Table 1). Phosphorus concentration increased during conversion of raw residues to biochar in rice bran, beech residues and pistachio shell by 98.7%, 141.7% and 97.3%, respectively. Limited information is available on phosphorus changes during the thermal decomposition process, but one study reported that phosphorus concentration increased with increasing heat-curing process from 250 to 800 °C. As well as, 100% phosphorus was recovered in the biochar from sewage sludge at 450 °C [17] .

Cation exchange capacity (CEC) of biochar

Results of comparison of means by t-test showed a significant effect on increasing CEC through conversion of plant residues to biochar (Table 1). So that CEC increased during the conversion of rice bran, beech residues and pistachio shell to biochar by 253.6%, 185.8% and 123%, respectively.

Biochar Ca, Mg, and K concentrations

The results of comparison of means by t-test showed a significant difference between the concentrations of Ca, Mg and K in plant residues and their biochar (P <0.01). As concentrations of Ca, Mg and K increased during the conversion of rice bran, beech residues and pistachio shell to biochar. Increased concentration rates of Ca, Mg and K in rice bran during conversion to biochar were 59.52, 85 and 41.5%, respectively. Concentrations of Ca, Mg and K from beech tree residues increased by 88.3%, 58.33% and 48.86%, respectively. Concentrations of Ca, Mg and K in biochar increased during conversion of pistachio shell to biochar by 85.45%, 27.65% and 33.17%, respectively. The nutrients of Ca, Mg and K existed in plant residues accumulate in the biochar ash as a result of burning. Burning the plant residues at temperatures of 400-450 °C increased the biochar ash content. Plants need large amounts of nutrients such as Ca, Mg, K and P for optimal growth. Organic matter is also essential for soil fertility and stable aggregates [8]

Table 1: Comparison of the mean concentrations of carbon (C), nitrogen (N) and phosphorus (P) and cation exchange capacity (CEC) of the primary residues and their biochar

Residue type	Material level	C	N	P	CEC
		%			cmol/kg
	Raw residue	37.76	1.35	0.77	9.79
	Biochar	47.07	1.04	1.53	34.62
t-value		10.53**	9.81**	10.75**	46.45**
	Raw residue	41.89	1.61	0.84	14.78
	Biochar	68.22	1.16	2.03	42.51
t-value		73.78**	12.16**	6.35**	23.99**
Pistachio shell residue	Raw residue	43.32	1.52	0.74	12.6
	Biochar	66.23	1.12	1.46	28.1
t-value		81.31**	12.78**	13.76**	15.48**

**, significant at $P < 0.01$.

Table 2: Comparison of mean concentrations of calcium (Ca), magnesium (Mg), Potassium (K) of plant residues and their biochar

Residue type	Material level	Ca	k	mg
		%		
	Raw residue	0.1	2.53	0.042
	Biochar	0.185	3.58	0.067
t-value		56.90**	14.2**	13.55**
	Raw residue	0.12	2.58	0.06
	Biochar	0.226	3.79	0.095
t-value		100.24**	14.78**	33.76**
Pistachio shell residue	Raw residue	0.11	2.11	0.047
	Biochar	0.204	2.81	0.06
t-value		26.17**	10.58**	3.6**

**, significant at $P < 0.01$.

The effect of biochar consumption on microbial respiration of two acidic and calcareous soils

The value of carbon emitted as CO_2 by the addition of different biochars at 2% and 4% levels in two acidic and calcareous soils over a period of 183 days is presented in Figures 1, 2, 3 and 4. As can be seen, the value of carbon emitted as CO_2, which indicates microbial respiration, or, in other words, the value of soil organic carbon mineralization, increases over time.

Crohn et al. (2003) found that decomposition of organic matter added at any depth of soil was faster early in the period, probably due to the availability of easy degradable materials in organic matter, but the decomposition rate decreases over time due to the reduction of degradable materials. The decrease in CO_2 can be attributed to the resistance of carbon-containing plant residues to degradation and undesirable environmental factors.

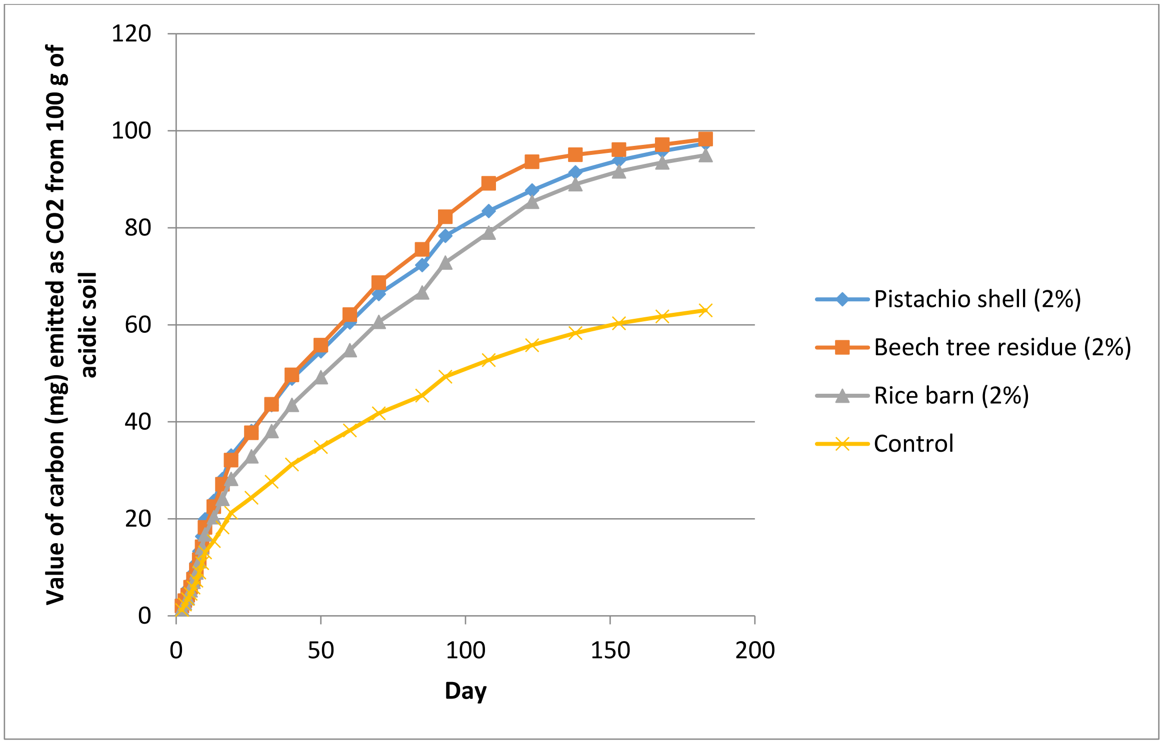

Figure 1: Effect of type and levels of biochar on carbon emitted as CO_2 from acidic soils

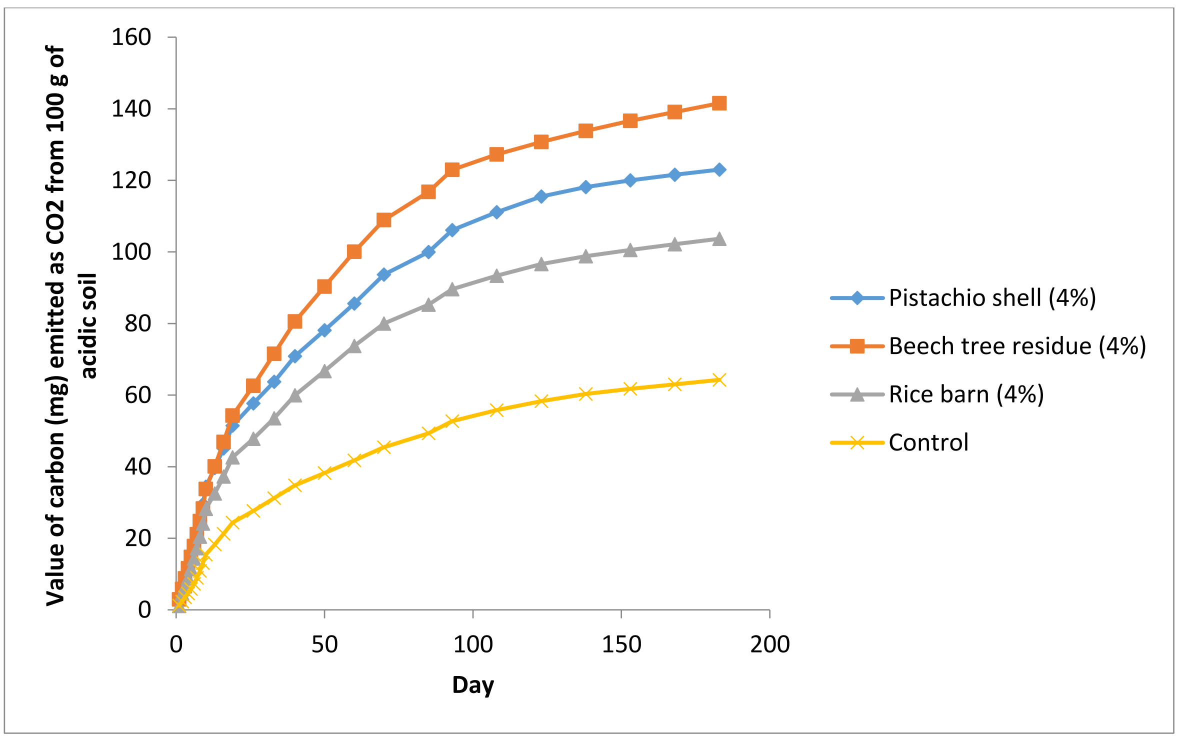

Figure 2: Effect of type and levels of biochar on carbon emitted as CO_2 from acidic soils

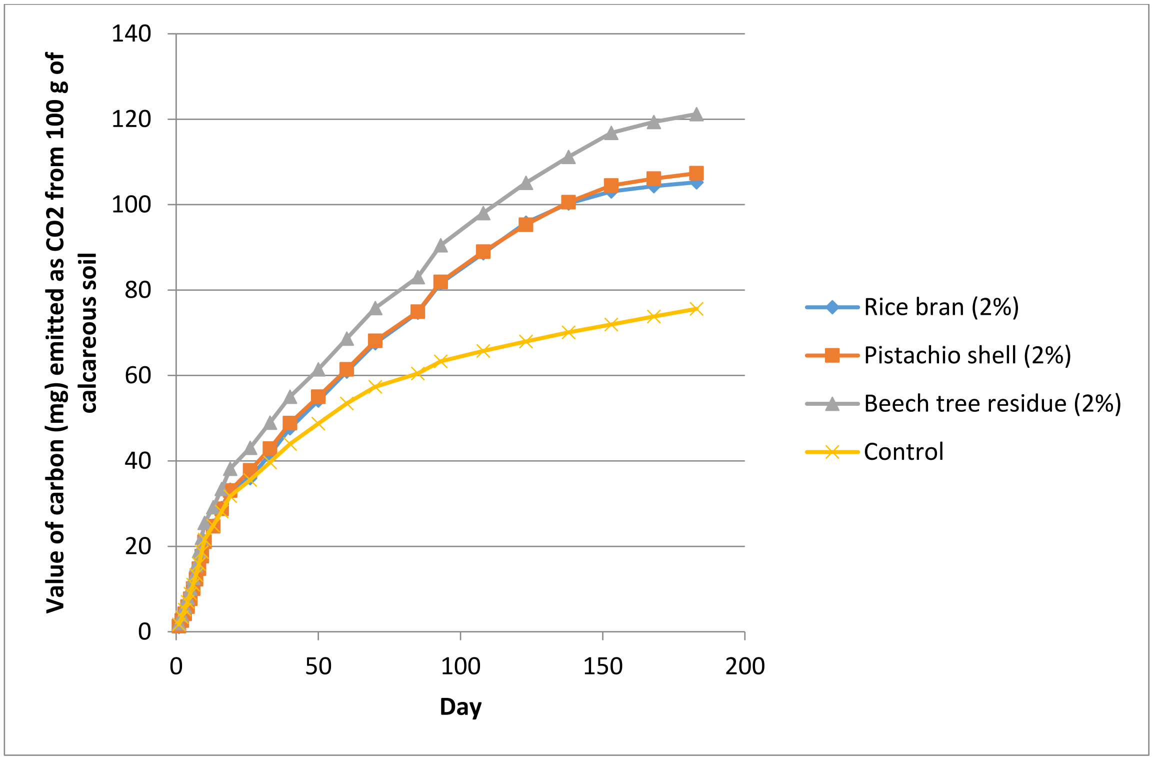

Figure 3: Effect of type and levels of biochar on carbon emitted as CO_2 from calcareous soils

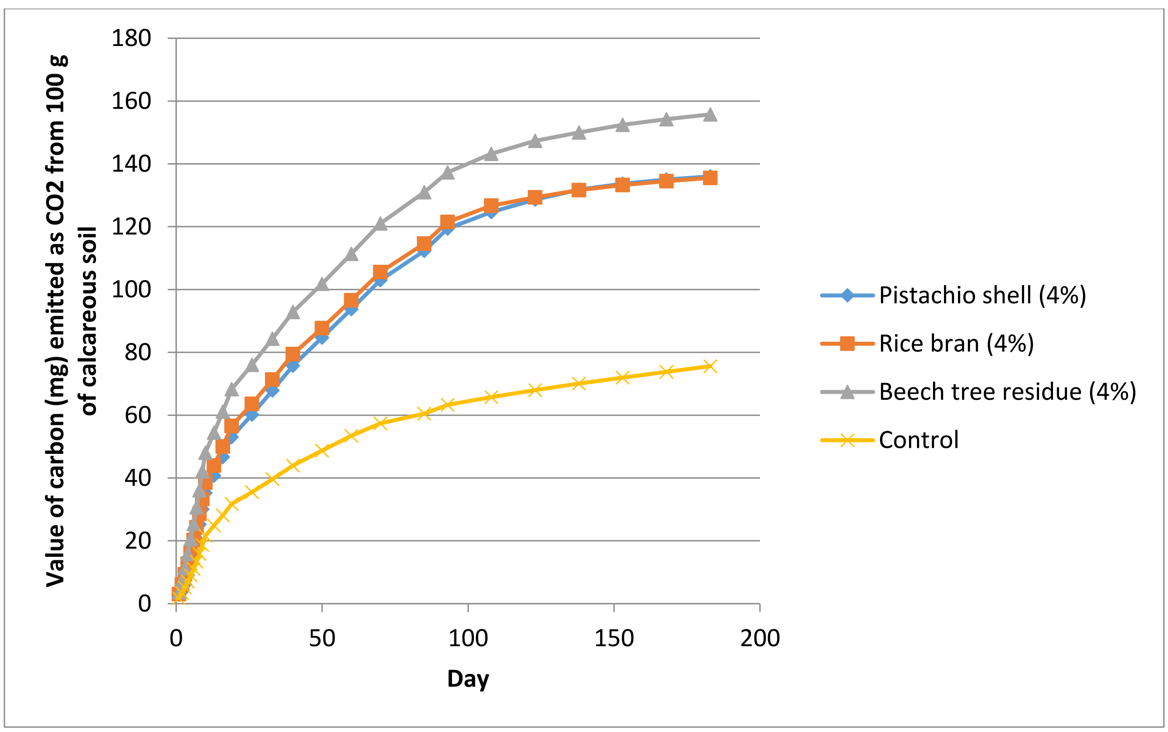

Figure 4: Effect of types and levels of biochar on carbon emitted as CO_2 from calcareous soils

Discussion and Cunclusion

Evaluation of the effect of biochar utilization on soil chemical and biological properties revealed that biochar utilization significantly increased the amount of organic carbon, total nitrogen, available phosphorus, exchangeable cations and cation exchange capacity in both acidic and calcareous soils.

According to the results, it can be concluded that pistachio shell biochar in both acidic and calcareous soils had a significant effect on the improvement of soil chemical and biological properties.

High temperatures result in the formation of high carbon content biochar with aromatic structure that is resistant to microbial and physical degradation [18] . Wu et al. (2012) reported that the value of biochar-aromatic carbon increased by increasing the temperature of the thermal decomposition process from 300 to 500 °C, which is resistant to microbial decomposition. Biochar is mainly composed of amorphous compounds [19] . Studies show that biochars produced at low temperature have aliphatic carbon that is readily degradable and can be beneficial to microorganisms by affecting the soil microbial community [13] . Scientists believe that the addition of high-stability biochar to soil increases carbon sequestration in the soil and creates a rich source of organic carbon in the soil [6] .

Combustion of plant residues at high temperatures will increase the rate of CEC of their biochar . Low-temperature biochar (400-450 °C) is extremely rich in nutrients and can affect soil properties such as water retention capacity and nutrients can be very useful for modifying soil chemical properties [13] .

Respiration is one of the main ways of wasting carbon and making changes in the storage of this element in the soil which is influenced by factors such as groundwater level, soil and air temperature, soil moisture, precipitation, climate factors, microbial biomass, physical properties, sun radiation, soil type, plant type, root respiration and discharge, land use type, drainage conditions and type of management operation (Post, 2000), which soil management and subsequently climate are certainly the most important factors affecting soil organic carbon content [20] .

Biochar has great potential for carbon sequestration in soil. However, some studies have shown that the addition of biochar to the soil increases soil organic matter and increases CO_2 emissions from the soil as a result of increased soil organic matter [21] .

The results showed that the highest amount of carbon loss as CO_2 was observed in acidic soil from the soil treated with 4% beech tree residue biochar and the lowest amount of carbon loss was observed in the soil treated with 2% rice bran biochar.

The results showed that the highest amount of carbon loss as CO_2 was observed in calcareous soils treated by 4% beech tree residue biochar and the lowest amount of carbon loss was observed in the soil treated with 2% rice bran biochar.

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