Cation Behaviour in Calcareous and Gypsiferous Soils Amended with Compost and Biochar

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Abstract

The aim of the study was to investigate the role of organic amendments (compost and biochar) in the sustainability of agricultural soils of two soil types. The study was conducted on two different soils (calcareous and gypsum), with compost and biochar added at four levels (0% and 2% compost, 2% biochar, and 1% compost + 1% biochar) by soil weight, the soil was packed into plastic columns (25 cm long and 7 cm in diameter). The experiment was conducted by adding irrigation water (river water) to each column in a volume equivalent to the pore volume, and alternating wetting was carried out for ten cycles, with a seven-day interval between each cycle. The soluble cations (Ca^{+2}, Mg^{+2}, Na^{+} and K^{+}) were measured in the soil samples after the first, fifth and tenth cycles. The results indicated that there was a clear variation in the concentrations of these ions in the study soils when different irrigation intervals and different application rates of organic amendments were used. With regard to the levels of organic amendments added to the study soils, these played a clear role in increasing soluble Ca^{+2} values; the results showed that the treatment combining compost and biochar was superior in reducing soluble calcium values, achieving a statistically significant reduction of 10.76% compared to the control treatment. As for soluble Mg^{+2}, the results showed that the treatment involving the mixture of compost and biochar led to an increase in its concentration, outperforming the other treatments and achieving a statistically significant increase of 17.83%. When comparing the two study soils, the variation in gypsum soil was generally higher than that in calcareous soil; As for the irrigation intervals, there was a gradual increase in the values of soluble magnesium and potassium with an increase in the number of irrigation intervals, starting from (C_1) after 7 days up to (C_{10}) after 70 days, conversely, there was a gradual decrease in the levels of dissolved calcium and sodium as the number of irrigation cycles increased, starting from (C_1) after 7 days up to (C_{10}) after 70 days.

Keywords: compost, biochar, cations in soil

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Introduction

The use of certain organic amendments, such as compost and biochar, has gained prominence in recent times as effective tools for improving various soil properties and enhancing agricultural sustainability [1]. Consequently, the world has moved towards reducing the use of chemical fertilizers due to their negative effects on the soil environment, and towards using organic amendments because of their positive effects on various soil properties [2].Like other organic compounds, compost plays a significant role in soil chemistry; as compost possesses a high negative charge that attracts positive ions from macro- and micronutrients, with its cation exchange capacity ranging from 300 to 1400 Cmol kg^{-1} [3]. Furthermore, it has the ability to chelate micronutrients, reduce the toxicity of heavy metals and lower soil reactivity, particularly in the rhizosphere, as a result of the release of hydrogen ions and various organic acids. It also plays a role in the degradation, activity and persistence of pesticides [4].In other words, one of the most important benefits of compost in soil is that it increases the soil's cation exchange capacity (CEC), which is the amount of cations exchanged per unit mass of dry soil, expressed in Cmole kg^{-1} of soil; this is achieved through the contribution of organic matter, which accounts for approximately 25 – 90% of the soil's ability to exchange positive ions (CEC) in the topsoil [5]. There is a positive correlation between the cation exchange capacity of soil and its clay and organic matter content; it increases with the addition of organic matter, which contributes to the increased availability of nutrients in the soil [6].Like any organic matter in the soil, compost is essential for maintaining soil fertility and reducing nutrient loss. Compost is a good organic fertilizer as it contains various nutrients and organic materials; organic matter acts as a vital medium for the activity of the various organisms living in the soil environment, as it provides nutrients, improves the soil's ability to retain moisture, and provides better aeration for seed germination and plant root development [7].Furthermore, one of the factors contributing to increased productivity and sustainable agriculture is the use of compost; moreover, it is one of the solutions available to farmers to address the issue of declining soil fertility, which often leads to reduced crop yields and makes crops susceptible to pests and diseases due to poor growing conditions [8]. Biochar is a sustainable soil conditioner that plays a positive role in crop growth; in general, it plays an important role in improving certain soil properties, such as the soil's ability to retain moisture and nutrients [9].One promising alternative method for reducing the use of chemical fertilizers in soils suffering from low fertility is to convert plant and crop residues into biochar to improve soil fertility and enhance its chemical and physical properties [10].

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As organic carbon sequestration is crucial for improving the soil environment and its properties, the addition of amendments containing high levels of organic carbon, such as biochar, can enhance various soil properties [11].Adding a mixture of compost and biochar to the soil has positive effects on soil properties; however, through different mechanisms, the addition of biochar can lead to a reduction in the average turnover rate of fine organic matter, thereby allowing more organic carbon to be stored over the long term [12].The high carbon content of biochar is most likely due to its slow rate of biodegradation and the length of time it remains in the soil; Biochar affects soil carbon due to its high content of stable carbon, whilst composted organic manure has a stronger effect on soil pH and cation exchange capacity [13]. Biochar stored for a long period in the soil showed a decrease in pH, in contrast to the long-term effect of composted organic fertilizers in increasing soil pH and cation exchange capacity [14].The aim of this study is to evaluate the role of organic amendments (compost, biochar, and a mixture of the two) in the behavior and movement of dissolved cations (calcium, magnesium, sodium and potassium).

Materials and Methods

1. Selection of study sites

The study covered two sites with different soil types (one site comprising calcareous soil and the other gypsum soil) in the province of Nineveh, Iraq. Soil samples were collected from the surface layer (20 cm) for routine analysis. The soil samples were air-dried, ground using a wooden pestle, and sieved through a 2 mm sieve. The quantities of the three fractionsclay, silt and sandas well as total calcium carbonate, organic matter, cation exchange capacity, pH and electrical conductivity (EC) were determined using the methods described [16]. The laboratory work was carried out in the Soil Science Laboratory of the Department of Soil Science and Water Resources / University of Mosul/ Iraq. As shown in table (1).

2. Testing the effect of compost and biochar on some chemical properties of soil in soil columns

After collecting the study samples from the field, they were ground and sieved through a 4 mm mesh sieve, then placed in plastic columns (25 cm long and 7 cm in diameter). Compost made from plant waste was added at a level of (2%) of the soil weight in three columns, after being thoroughly mixed with the soil before filling the plastic columns. Biochar made from bamboo was also added at a level of (2%) of the soil weight in three columns [16], and was thoroughly mixed with the soil before filling the plastic columns.Biochar (1%) and compost (1%) by weight of the soil were added to three columns, and these were thoroughly mixed with the soil before filling the plastic columns.

Distilled water was then added to each column in a volume equivalent to the pore volume for soil C, and the columns were left for one month to allow the organic matter in the soil to decompose. Irrigation water was added to each column in a volume equivalent to the pore volume C (the pore volume was calculated by weighing the soil column when dry and then weighing it when saturated with water,the difference between the two weights is the pore volume), and the wetting process was carried out consecutively over ten cycles, with a seven-day interval between each cycle. Following the first (C_1), fifth (C_5) and tenth (C_{10}) cycles, the soil was removed from each column, air-dried, ground and sieved through a 2 mm sieve. The following cations soluble were then determined: calcium, magnesium, sodium and potassium.

Table (1): Some physical and chemical properties of the study soil

Traits	**Calcareous soil**	**Gypsum Soil**	**Unit**
Clay	427.0	277.0	$gm.kg^{-1}$
Silt	467.5	517.5	
Sand	105.5	205.5	
Texture	Silty Clay	Silty Loam	
Lime ($CaCO_3$)	320.0	240.0	$gm.kg^{-1}$
Gypsium ($CaSO_4.2H_2O$)	17.5	152.8	
Organic Matter (OM)	1.18	1.85	
Cation Exchange Capacity (CEC)	32.00	25.00	$Cmol.kg^{-1}$
Potential Hydrogen (pH)	7.50	7.10	
Electrical Conductivity (EC)	0.90	6.42	$dS.m^{-1}$
Calcium (Ca^{+2})	4.00	32.00	$meq.L^{-1}$
Magnesium (Mg^{+2})	3.25	22.00	
Sodium (Na^+)	1.20	9.23	
Potassium (K^+)	0.25	0.50	
Chloride (Cl^-)	2.00	20.00	
Bicarbonate (HCO_3^-)	3.75	6.00	
Sulfate ($SO_4^{=}$)	2.50	38.00	

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Results and Discussion

1. The effect of adding compost and biochar on the behaviour of cations

In order to investigate the role of organic amendments in the behavior of cations in two soil types (calcareous and gypsum), the study soils were irrigated over ten consecutive cycles under the influence of four different levels of compost and biochar (0%, 2% compost, 2% biochar, 1% compost + 1% biochar). The results of this study varied according to the levels of compost and biochar and the irrigation intervals.

1-1 Soluble Calcium (Ca^{2+})

The results shown in table (2) reveal a marked variation in soluble calcium values in both soils due to the effects of two-way interactions (soil type × application rate, soil type × irrigation cycles, application rate × irrigation cycles) and the three-way interaction (soil type × application rate × irrigation cycles). In general, the application treatments led to a reduction in soluble calcium values in both soils, with treatment (M) recording the lowest mean soluble calcium value; in the calcareous soil, the value reached (2.66) meq L^{-1}, representing a 21.99% reduction compared to the control treatment (W), which recorded a value of (3.41) meqL^{-1}. Similarly, in gypsum soil, the value for treatment (M) decreased to 28.33 mmol/L, representing a reduction of 9.57% compared to the control treatment (W), which recorded a value of 31.33 meqL^{-1}.

The superior performance of the biochar-compost mixture in reducing soluble calcium can be attributed to its effective role in increasing cation exchange capacity, which leads to the retention of calcium ions at the exchange sites rather than their remaining in the soil solution. Furthermore, the reduction in calcareous soils was more pronounced compared to gypsum soils due to the prevalence of calcium carbonate in these soils, as the high concentration of carbonate ions promotes chemical equilibrium that limits the dissolution of calcium in the solution, whereas the presence of gypsum in gypsum soils, which have higher solubility, maintains high levels of dissolved calcium.The results indicated a significant interaction effect between soil type and irrigation cycles on the mean values of soluble calcium; the highest values were recorded in the first cycle (C_1), reaching (3.43 and 31.50) meqL^{-1} for the calcareous and gypsum soils, respectively. In contrast, the values decreased to their lowest level in the tenth cycle (C_{10}), with an average of (2.75 and 27.87) meq L^{-1} for the calcareous and gypsum soils, respectively. Furthermore, it was found that there was a direct effect of the wetting cycles on reducing the dissolved calcium values; the highest values were recorded in the first cycle C_1 (17.46) meqL^{-1},

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then gradually decreased in the fifth cycle C_5 (16.25), with the lowest value occurring in the tenth cycle C_{10} (15.31). This is due to the role of repeated wetting cycles in promoting chemical equilibrium processes between the solid phase and the soil solution, whereby calcium is re-precipitated as sparingly soluble compounds such as calcium carbonate in calcareous soils and calcium sulphate in gypsum soils. In addition, its adsorption on the cation exchanges complex increases as a result of the activation of colloidal surfaces by the repeated expansion and contraction of soil particles [15].

Table (2) : Effect of adding compost, biochar and soil type on the soluble calcium (Ca^{2+})meq L^{-1}

Soil Type	Addition ratio	Hydration cycles			Soil Type × Addition ratio
		First C_1	Fifth C_5	Tenth C_{10}	
Calcareous	(W) 0%	4.00	3.00	3.25	3.41
	(C) 2%	3.50	3.50	2.75	3.25
	(B) 2%	3.25	2.75	2.75	2.91
	(M) 1%+1%	3.00	2.75	2.25	2.66
gypsum	(W) 0%	32.00	31.00	31.00	31.33
	(C) 2%	30.00	29.00	28.50	29.16
	(B) 2%	32.00	30.00	27.00	29.66
	(M) 1%+1%	32.00	28.00	25.00	28.33
L.S.D		1.085			0.626
					Soil Type Mean
Soil Type × Hydr. Cycles	Calcareous	3.43	3.00	2.75	3.06
	gypsum	31.50	29.50	27.87	29.62
L.S.D		0.542			0.313
					Add. ratio Mean
Addition ratio × Hydr. Cycles	(W) 0%	18.00	17.00	17.12	17.37
	(C) 2%	16.75	16.25	15.62	16.20
	(B) 2%	17.62	16.37	14.87	16.29
	(M) 1%+1%	17.50	15.37	13.62	15.50
L.S.D		0.767			0.443
Hydration cycles Mean		17.46	16.25	15.31	
L.S.D		0.383			

(W) 0% : Control **(C) 2%** : Compost **(B) 2%** : Biochar
(M) 1%+1% : Mix (1% Compost + 1% Biochar)

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Furthermore, statistical analysis showed that the interaction between the admixture ratio and the curing cycles had a significant effect on the dissolved calcium values; these values peaked in the W-C_1 treatment with an average of (18.00) meq L^{-1}, whilst the M-C_{10} treatment recorded the lowest values at (13.62) meq L^{-1}. Regarding the main effect of the additive treatments, the control treatment (W) significantly outperformed the others by recording the highest soluble calcium value of (17.37) meq L^{-1}. The superiority of the control treatment in recording the highest concentration of dissolved calcium is attributed to the absence of any soil-improving additives, which kept the calcium in a state of natural equilibrium with the soil solution without subjecting it to additional fixation or adsorption processes. On the other hand, the use of a mixture of biochar and compost in treatment (M) contributed to reducing the soluble calcium value to (15.50) meqL^{-1}, representing a 10.76% decrease compared to the control treatment (W) (Figure 1). This reflects the synergistic effect of these processes, where the mechanisms of adsorption, precipitation and ion exchange interact to reduce soluble calcium. This confirms the effectiveness of the biochar-compost mixture treatment in modifying the calcium balance in the soil and converting it from the soluble form to less mobile and more stable form. The results showed a significant three-way interaction between soil type, application rate and irrigation cycles on soluble calcium values, with the lowest soluble calcium value of (2.25) meq L^{-1} recorded in the M-C_{10} treatment in calcareous soil.

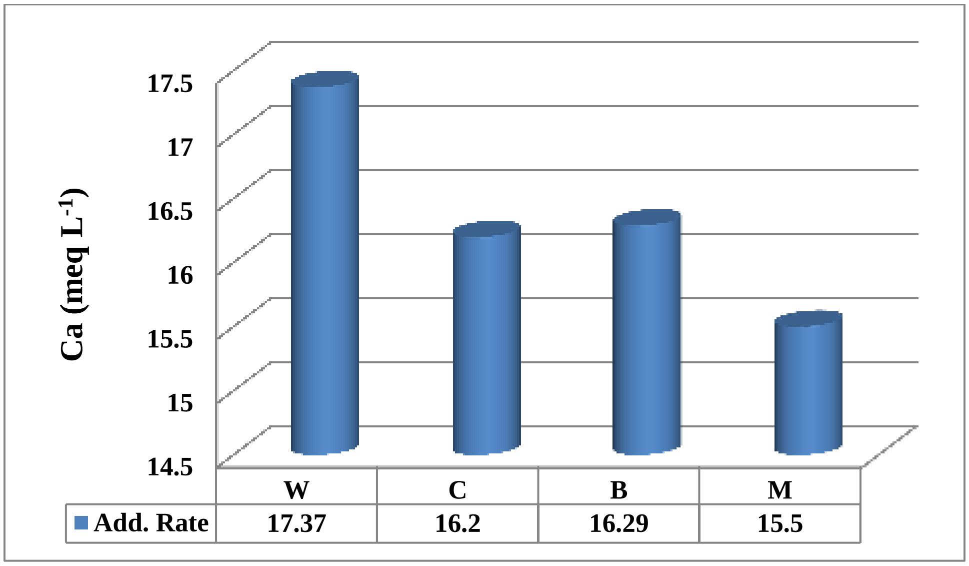

Figure (1): Effect of the additionrate on the average soluble (Ca^{2+}) values of the soils under study

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In contrast, these values reached their maximum, recording 32.00 mmolL^{-1} in gypsum soil, specifically in the W-C_1, B-C_1 and M-C_1 treatments. It is evident that the interaction between the three factors plays a decisive role in determining the fate of calcium in the soil, as the response varies depending on soil type, mineral characteristics, the nature of the addition and the number of wetting cycles, reflecting the complexity of calcium's geochemical behavior in the soil system [16].

1-2 Soluble Magnesium (Mg^{+2})

The data in table (3) show that the two-way interactions (soil type × application rate, soil type × irrigation cycles, application rate × irrigation cycles) and the three-way interaction (soil type × application rate × irrigation cycles) have a significant effect on the values of soluble magnesium in the soil. With regard to the two-way interaction between soil type and application rate, an increase in the mean values of soluble magnesium was observed in conjunction with an increase in application rates in both soil types. In calcareous soil, treatments (C), (B) and (M) recorded the highest values, with an average of (3.66) meq L^{-1}, achieving an increase of 12.61% compared to the control treatment (W), which had an average of (3.25) meq L^{-1}. In gypsum soil, treatment (M) outperformed the others, recording the highest average soluble magnesium value of (27.66) meqL^{-1} and an increase of 18.55% compared to the control treatment (W), which recorded (23.33) meqL^{-1}. The increase in soluble magnesium values with increasing application rates in both soils is attributed to the direct and indirect effects of the additives in promoting the release of nutrients. These additives serve as an additional source of magnesium, in addition to their role in stimulating biological processes and increasing the decomposition of organic matter, which leads to the release of magnesium into the soil solution and an increase in its concentration in the soluble form.The results in the same table indicate that the interaction between soil type and irrigation cycles had a significant effect on the mean values of soluble magnesium; with the highest values recorded in the tenth cycle (C_{10}), reaching (3.68 and 26.75) meqL^{-1} for the calcareous and gypsum soils, respectively. In contrast, the lowest values were recorded in the first cycle (C_1), with averages of (3.43 and 24.75) meqL^{-1} for the calcareous and gypsum soils, respectively, Furthermore, the wetting cycles had an independent and significant effect on the dissolved magnesium values, with a gradual increase in the overall average values observed over the course of the cycles, recording (14.09, 14.53 and 15.21) meq L^{-1} for the first, fifth and tenth cycles, respectively.

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Table (3) : Effect of adding compost, biochar and soil type on the soluble magnesium (Mg^{2+}) meq L^{-1}

Soil Type	Addition ratio	Hydration cycles			Soil Type × Addition ratio
		First C_1	Fifth C_5	Tenth C_{10}	
Calcareous	(W) 0%	3.25	3.00	3.50	3.25
	(C) 2%	3.50	3.75	3.75	3.66
	(B) 2%	3.50	3.75	3.75	3.66
	(M) 1%+1%	3.50	3.75	3.75	3.66
Gypsum	(W) 0%	22.00	23.00	25.00	23.33
	(C) 2%	24.00	25.00	26.00	25.00
	(B) 2%	26.00	26.00	28.00	26.66
	(M) 1%+1%	27.00	28.00	28.00	27.66
L.S.D		0.940			0.543
					Soil Type Mean
Soil Type × Hydr. Cycles	Calcareous	3.43	3.56	3.68	3.56
	gypsum	24.75	25.50	26.75	25.66
L.S.D		0.470			0.271
					Add. ratio Mean
Addition ratio × Hydr. Cycles	(W) 0%	12.62	13.00	14.25	13.29
	(C) 2%	13.75	14.37	14.87	14.33
	(B) 2%	14.75	14.87	15.87	15.16
	(M) 1%+1%	15.25	15.87	15.87	15.66
L.S.D		0.665			**0.384**
Hydration cycles Mean		14.09	14.53	15.21	
L.S.D		**0.332**			

(W) 0% : Control **(C) 2%** : Compost **(B) 2%** : Biochar
(M) 1%+1% : Mix (1% Compost + 1% Biochar)

Successive irrigation cycles lead to increased dissolution of certain secondary minerals and magnesium-bearing compounds, as well as the activation of chemical weathering processes, which contributes to the release of additional amounts of magnesium into the soil solution [17].

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Furthermore, the interaction between the addition rate and the irrigation cycles had a significant effect on the dissolved magnesium concentrations; the highest average concentration of (15.87) meq L^{-1} was recorded in the M-C_{10}, B-C_{10} and M-C_5 treatments, whilst the lowest mean was recorded in the W-C1 treatment at (12.62) meqL^{-1}. With regard to the independent effect of the addition rate, the treatment combining biochar and compost (M) outperformed the others, recording the highest average of (15.66) meqL^{-1}, thereby achieving a significant increase of 17.83% compared to the control treatment (W), which had an average of (13.29) meq L^{-1} (Figure2). This indicates that when the two materials are used together, a clear synergistic effect is evident, as the compost acts to increase the magnesium source and its solubility, whilst the biochar provides temporary binding sites that reduce its loss and regulate its release. Furthermore, the interaction between organic matter and the active surfaces of biochar may lead to a reduction in the fixation of magnesium in insoluble forms, thereby keeping a greater proportion of it in solution.

Finally, statistical analysis of the three-way interaction between soil type, application rate and irrigation cycles revealed a significant effect on soluble magnesium levels. In this context, the highest soluble magnesium levels were recorded in gypsum soils at treatments B-C_{10}, M-C_{10} and M-C_5, with a common value of (28.00) meq L^{-1} , whilst the lowest value was recorded in calcareous soil at treatment W-C_5, amounting to (3.00) meq L^{-1}. The high values in gypsum soils are attributed to their saline nature and the high ionic strength of the soil solution resulting from the presence of calcium sulphate, which enhances the displacement of magnesium from exchange sites into the soil solution as a result of ionic competition .Biochar and compost contribute to increasing the release of magnesium, either as a direct source (compost) or by improving cation exchange and increasing the effective surface area (biochar). Furthermore, repeated wetting cycles, particularly during the tenth cycle, enhance weathering and dissolution processes and break down the soil structure, thereby releasing greater quantities of magnesium into the solution. The low magnesium values in calcareous soils, particularly in the W-C_5 treatment, are attributed to the predominance of calcium carbonate, which limits the solubility of many divalent cations, including magnesium, due to chemical equilibria that tend to precipitate or stabilize them. Furthermore, the absence of additives in the control treatment (W) reduces the available sources of magnesium, and the average number of wetting cycles (the fifth cycle, C_5) may not be sufficient to cause a significant release of magnesium compared to higher cycles [18].

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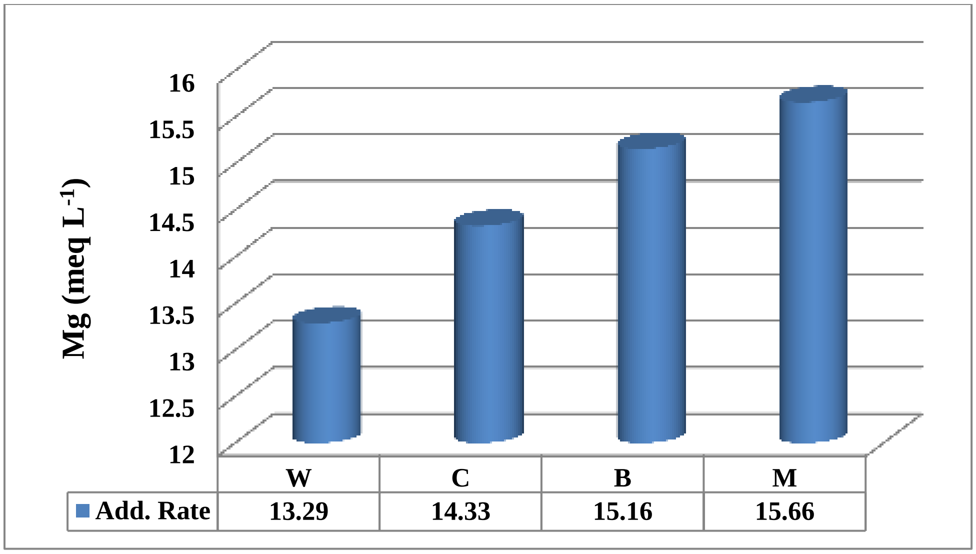

Figure (1): Effect of the additionrate on the average soluble (Mg^{+2}) values of the soils under study

1-3 Soluble Sodium (Na^{+})

The results of the statistical analysis presented in table [4] indicate that the two-way interactions (soil type × application rate, soil type × irrigation cycles, application rate × irrigation cycles) and the three-way interaction (soil type × application rate × irrigation cycles) had a significant effect on the values of soluble sodium in the soil. With regard to the two-way interaction between soil type and application rate, a clear significant effect was recorded on the mean values, where a general decrease in soluble sodium concentrations was observed in response to increased application rates in both soil types under study, Treatments (M) and (B) performed significantly better, recording the lowest mean soluble sodium values compared to the other treatments. In calcareous soil, the value decreased to 0.82 meq L^{-1} , representing a reduction of 20.38% compared with the control treatment (W), which had an average of (1.03) meq L^{-1}. Similarly, in gypsum soil, treatment (M) achieved the lowest value of (7.31) meq L^{-1} and a reduction of 21.08% compared to the control treatment (W), which recorded (9.25) meq L^{-1}. Consequently, the interaction between soil type and the rate of application clearly demonstrates that increasing the application rate, particularly the treatment combining biochar and compost, effectively contributes to reducing soluble sodium through increased adsorption, replacement and leaching processes, thereby improving the ionic balance in the soil and reducing the risk of

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salinization or sodicity in the soil environment [19].

Table (4) : Effect of adding compost, biochar and soil type on the dissolved sodium (Na^+) meq L^{-1}

Soil Type	Addition ratio	Hydration cycles			Soil Type × Addition ratio
		First C_1	Fifth C_5	Tenth C_{10}	
Calcareous	(W) 0%	1.21	0.95	0.95	1.03
	(C) 2%	0.91	0.86	0.82	0.86
	(B) 2%	0.86	0.82	0.78	0.82
	(M) 1%+1%	0.91	0.78	0.78	0.82
Gypsum	(W) 0%	9.50	9.34	8.91	9.25
	(C) 2%	8.26	8.08	7.91	8.08
	(B) 2%	8.47	7.95	7.60	8.00
	(M) 1%+1%	7.82	7.39	6.73	7.31
L.S.D		0.215			0.124
					Soil Type Mean
Soil Type × Hydr. Cycles	Calcareous	0.97	0.85	0.83	0.88
	gypsum	8.51	8.19	7.78	8.16
L.S.D		0.107			0.062
					Add. ratio Mean
Addition ratio × Hydr. Cycles	(W) 0%	5.35	5.14	4.93	5.14
	(C) 2%	4.58	4.47	4.36	4.47
	(B) 2%	4.66	4.38	4.19	4.41
	(M) 1%+1%	4.36	4.08	3.75	4.06
L.S.D		0.152			0.087
Hydration cycles Mean		4.74	4.52	4.31	
L.S.D		0.076			

(W) 0% : Control **(C) 2%** : Compost **(B) 2%** : Biochar
(M) 1%+1% : Mix (1% Compost + 1% Biochar)

The same table shows that statistical analysis indicates a significant two-way interaction between soil type and irrigation cycles on the mean values of dissolved sodium. A gradual decrease in these values was observed as the irrigation cycles progressed (from the first cycle C_1 through the fifth cycle C_5 to the tenth cycle C_{10}). The highest values were recorded in the first cycle

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C_1, with averages of (0.97 and 8.51) meqL^{-1} for the calcareous and gypsum soils, respectively.

In contrast, these values declined to their lowest levels in the tenth cycle (C_{10}), recording (0.83 and 7.78) meqL^{-1} for the calcareous and gypsum soils, respectively. Furthermore, the results showed a significant independent effect of irrigation cycles on the mean values, with the highest mean in the first cycle C_1 (4.74) meq L^{-1}. It then decreased gradually and significantly in the fifth cycle (C_5), recording (4.52) meq L^{-1}, reaching its lowest value in the tenth cycle (C_{10}) with an average of (4.31) meq L^{-1}. This gradual and significant decrease in dissolved sodium concentration with increasing irrigation cycles is attributed to the cumulative effect of leaching and ionic displacement processes accompanying successive irrigation periods, leading to increased transport of dissolved salts. This results in the loss of a portion of the sodium outside the soil's reaction zone, particularly under drainage conditions that allow the leaching process to occur repeatedly [20].

In the same context, statistical analysis revealed a significant effect of the two-way interaction between the addition rate and the irrigation cycles on soluble sodium values, with the highest mean recorded at the interaction in the control treatment for the first cycle (W-C_1), amounting to (5.35) meq L^{-1}, whilst the lowest mean was recorded in the tenth cycle treatment (M-C_{10}), falling to (3.75) meq L^{-1}. As for the main effect of the addition treatments, the treatment combining biochar and compost (M) performed significantly better, recording the lowest overall mean of (4.06) meq L^{-1}, thereby achieving a statistically significant reduction of 21.01% compared to the control treatment (W), which recorded the highest average of (5.14) meq L^{-1} (Figure3). This is due to the synergistic effect of biochar and compost, which combines increased adsorption efficiency (due to biochar) and enhanced dissolution, replacement and leaching processes (due to compost), which explains the significant reduction compared to the control treatment, which lacked these enhanced effects, leaving the sodium in a more soluble state.

The three-way interaction (soil type × application rate × irrigation cycles) and the results of the statistical analysis revealed a significant effect on the values of dissolved sodium in the soil. This effect was evident in the clear variation in the means, with the highest concentration of soluble sodium recorded at (9.50) meq L^{-1} in the control treatment W-C_1 within the gypsum soil. In contrast, calcareous soils showed a high response to the treatments, reducing soluble sodium concentrations to their lowest levels, with treatments M-C_{10}, B-C_{10} and M-C_5

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recording a significant decrease with an average of (0.78) meq L^{-1}.

The clear disparity between the highest and lowest values reflects the high sensitivity of sodium behavior to the interaction between the three factors, whereby organic amendments, combined with an increase in the number of wetting cycles, lead to a significant reduction in its soluble concentration in calcareous soils, whilst gypsum soils remain more susceptible to its increase in the absence of these amendments [16)].

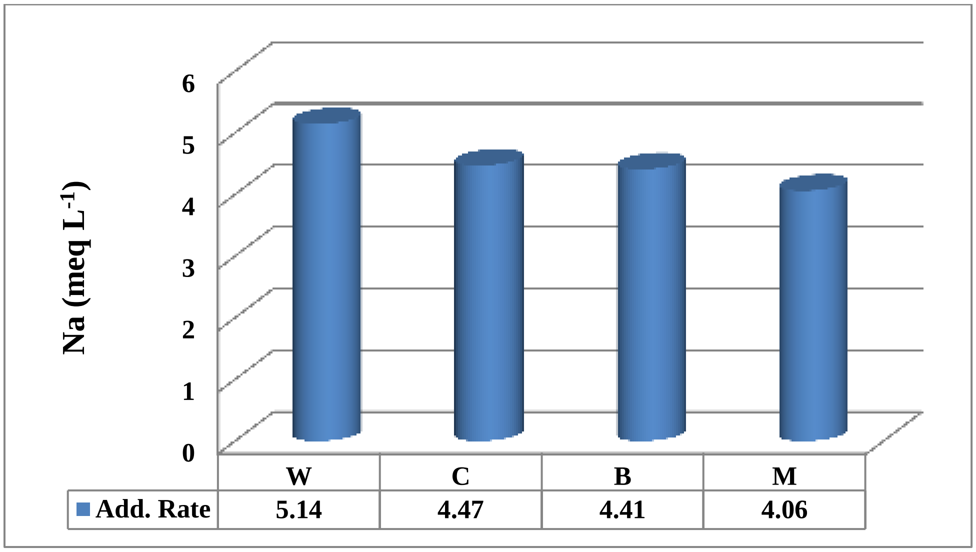

Figure (1): Effect of the additionrate on the average soluble (Na^+) values of the soils under study

1-4 Soluble Potassium (K^+)

Table (5) shows a clear response in soluble potassium values to the two-way and three-way interactions of the factors studied (soil type, application rate, and irrigation cycles). Analysis of the two-way interaction between soil type and application rate reveals a general trend towards higher concentrations of soluble potassium as application rates increase in both soil types. This response reached its maximum at treatment (M), where it was highest in the calcareous soil, achieving (0.46)meqL^{-1}, an increase of 58.62% compared to the control treatment (W), which was 0.29 meqL^{-1}. Similarly, treatment (M) in the gypsum soil recorded the highest concentrations at (0.84) meq L^{-1}, exceeding the control treatment (W) by 50.00%, which yielded (0.56) meq L^{-1}. The increase in dissolved potassium concentration with increasing application rates in both soils is attributed to the direct and indirect effects of the additives, particularly in

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the compost-biocoal mixture, in increasing the availability of potassium in the soil solution. as compost is a source of macronutrients, including potassium; its decomposition releases additional amounts into the dissolved phase, thereby gradually increasing its concentration in the soil solution as the application rates increase [21].

Table (5) : Effect of adding compost, biochar and soil type on the dissolved potassium (K^+) meq L^{-1}

Soil Type	Addition ratio	Hydration cycles			Soil Type × Addition ratio
		First C_1	Fifth C_5	Tenth C_{10}	
Calcareous	(W) 0%	0.25	0.30	0.33	0.29
	(C) 2%	0.40	0.46	0.48	0.44
	(B) 2%	0.35	0.43	0.46	0.41
	(M) 1%+1%	0.41	0.48	0.51	0.46
Gypsum	(W) 0%	0.51	0.56	0.61	0.56
	(C) 2%	0.64	0.71	0.76	0.70
	(B) 2%	0.69	0.74	0.79	0.74
	(M) 1%+1%	0.79	0.84	0.89	0.84
L.S.D		0.058			0.033
					Soil Type Mean
Soil Type × Hydr. Cycles	Calcareous	0.35	0.41	0.44	0.40
	gypsum	0.65	0.71	0.76	0.71
L.S.D		0.029			0.016
					Add. ratio Mean
Addition ratio × Hydr. Cycles	(W) 0%	0.38	0.43	0.47	0.42
	(C) 2%	0.52	0.58	0.62	0.57
	(B) 2%	0.52	0.58	0.62	0.57
	(M) 1%+1%	0.60	0.66	0.70	0.65
L.S.D		0.041			0.023
Hydration cycles Mean		0.50	0.56	0.60	
L.S.D		0.020			

(W) 0% : Control **(C) 2%** : Compost **(B) 2%** : Biochar
(M) 1%+1% : Mix (1% Compost + 1% Biochar)

The results in the table show a statistically significant interaction effect between (soil type × irrigation cycles) on the mean values of dissolved

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potassium in the soil, The general trend of these results is evident in the upward trend of concentrations as the irrigation cycles progress, with the first cycle (C_1) recording the lowest levels of soluble potassium at (0.35 and 0.65) meq L^{-1} for the calcareous and gypsum soils, respectively. Meanwhile, these values continued to rise gradually, peaking in the tenth cycle (C_{10}) with the highest concentrations of (0.44 and 0.76) meq L^{-1} for the same two soils, respectively.

This increasing trend is confirmed by the independent effect of irrigation cycles on dissolved potassium values, where a clear proportional response was observed with successive cycles, with overall averages rising from (0.50)meq L^{-1} in the first cycle, through (0.56)meq L^{-1} in the fifth cycle, to a maximum average of (0.60)meq L^{-1} in the tenth cycle. This is due to the repetition of wetting periods, which play a pivotal role in increasing the activity of physical and chemical processes within the soil body, including the weathering of certain potassium-containing minerals such as feldspar and clay minerals, thereby contributing to the release of additional amounts of potassium into the soil solution. On the other hand, the repetition of wetting cycles may limit the fixation of potassium in non-exchangeable sites within clay minerals, particularly with the continuation of repeated water saturation, thereby increasing its soluble fraction [20].

In the same context, the results showed a clear significant response in dissolved potassium concentrations due to the interaction between the addition rate and the irrigation cycles. The general behavior of this interaction is evident in the positive synergy between these two factors in increasing potassium release, with concentrations peaking at a highest average of (0.70) meq L^{-1} in the M-C_{10} treatment, in clear contrast to the lowest concentration recorded of (0.38) meq L^{-1} in the W-C_1 treatment. Furthermore, when evaluating the independent effect of the addition treatments, the clear superiority of the treatment combining biochar and compost (M) in improving the soil's soluble potassium content is evident, as it achieved the highest overall average of (0.65) meq L^{-1} , thereby achieving a substantial increase of 54.76% compared to the control treatment (W), which recorded only (0.42) meq L^{-1} (Figure4). The significant increase in the mixed treatment clearly reflects the effectiveness of this combination in improving the potassium balance in the soil, thereby increasing its availability to plants and improving soil fertility in general (22).

To sum up the effects of the experimental factors, the three-way interaction between (soil type, application rate, and irrigation cycles) proved to be statistically significant in determining soluble potassium levels. The general behavior of this interaction is characterized by the attainment of the maximum possible response when the best experimental conditions coincide, with concentrations rising to their highest levels of (0.89) meq L^{-1} in gypsum soil under the influence of the $M\text{-}C_{10}$ treatment. Conversely, these values declined to a minimum of (0.25)meq L^{-1} in calcareous soil under the control treatment $W\text{-}C_1$. This wide variation confirms the complementary and cumulative role of these combined factors in determining potassium levels and its availability in the soil solution.

The significant impact of this interaction stems from the complex reactive nature governing potassium behavior within the soil system; this interaction reflects the combined ability of optimal conditions to enhance the transfer of potassium from the solid to the liquid phase or to limit its retention therein, depending on the nature of the treatments [16].

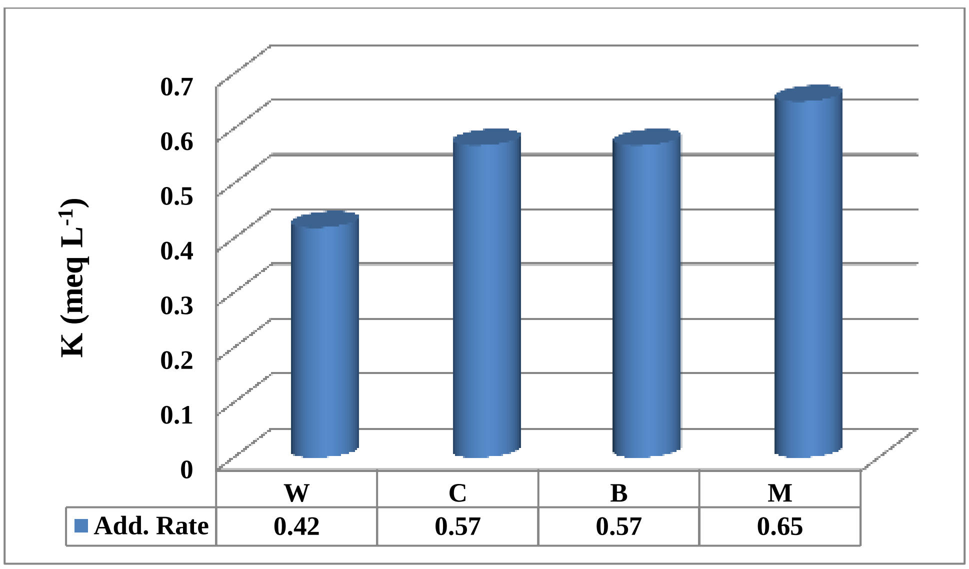

Figure (1): Effect of the addition rate on the average soluble (K^+) values of the soils under study

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