Effect of treatment with potassium polyacrylate, biochar, and organic fertilizer on the physiological characteristics of *Eruca sativa* grown in sandy soil

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Abstract

The study aimed to evaluate the effect of poultry manure, potassium polyacrylate, and biochar on improving the physical and chemical properties of the experimental soil, as well as to investigate the individual and combined effects of these amendments on certain physiological and chemical characteristics of rocket plant (*Eruca sativa* L.) grown in sandy soil during the autumn season of 2024 in Al-Muqdadiyah District, Diyala Province. The experiment was conducted according to a Randomized Complete Block Design (RCBD) with three factors, including organic fertilizer at two levels (0 and 10 t ha^{-1}), potassium polyacrylate at three concentrations (0, 50, and 100 kg ha^{-1}), and biochar at three concentrations (0, 10, and 20 t ha^{-1}) The results showed significant improvements in the physical and chemical properties of the soil. Soil pH increased from 7.39 to 7.53, electrical conductivity (EC) from 2.30 to 2.57 dS m^{-1}, field capacity (FC) from 8.00 to 13.93%, and organic matter (OM) from 1.18 to 1.46 g kg^{-1} soil. In addition, soil nitrogen content increased from 66.57 to 74.53 mg kg^{-1} soil, phosphorus from 10.27 to 11.64 mg kg^{-1} soil, and potassium from 180.60 to 188.95 mg kg^{-1} soil. The individual effect of organic fertilizer at 10 t ha^{-1} significantly increased the relative water content of leaves to 94.08%, while leaf nitrogen, phosphorus, and potassium contents reached 0.991, 0.125, and 1.236%, respectively, compared with the control treatment, which recorded 82.26, 0.686, 0.089, and 0.875%, respectively. Likewise, potassium polyacrylate at 100 kg ha^{-1} produced the highest mean values of relative water content (109.1%) and leaf nitrogen, phosphorus, and potassium contents of 1.143, 0.141, and 1.368%, respectively, compared with the control treatment. Similarly, biochar at 20 t ha^{-1} achieved the highest mean values of relative water content (100.9%) and leaf nitrogen, phosphorus, and potassium contents of 0.977, 0.123, and 1.245%, respectively, compared with the control treatment. The triple interaction among organic fertilizer at 10 t ha^{-1}, potassium polyacrylate at 100 kg ha^{-1}, and biochar at 20 t ha^{-1} recorded the highest mean relative water content of leaves (141.8%) compared with 60.00% in the control treatment. The same treatment also achieved the highest leaf contents of nitrogen, phosphorus, and potassium, reaching 1.537, 0.175, and 1.660%, respectively, compared with the control treatment, which recorded 0.505, 0.052, and 0.355%, respectively. The results indicate that the integration of organic fertilizer, biochar, and potassium polyacrylate effectively contributed to improving the fertility of sandy soil and enhancing plant water status and nutrient uptake, which was positively reflected in the physiological and nutritional performance of rocket plants under sustainable agricultural systems.

Keywords : *Eruca sativa* , biochar, potassium polyacrylate, poultry manure, physiological properties.

1- Introduction

Eruca sativa Mill. is considered one of the most important leafy vegetable crops belonging to the

Brassicaceae family and has gained increasing nutritional and medicinal attention due to its high nutritional value and rich content of bioactive compounds. Its leaves contain high levels of vitamins, minerals, and antioxidant compounds such as flavonoids, glucosinolates, and carotenoids, which contribute to promoting human health and preventing numerous diseases. *Eruca sativa* is also characterized by its rapid growth and adaptability to diverse environmental conditions, making it an economically and nutritionally important leafy crop. In addition, the global demand for leafy vegetables has increased in recent years as a result of the growing trend toward healthy dietary systems [43,7]. Reports of the Food and Agriculture Organization (FAO) have also indicated an increasing need to develop sustainable agricultural production systems capable of improving the productivity of leafy vegetable crops under resource-limited environments, particularly in arid and semi-arid regions that largely depend on sandy soils [17].

Sandy soils are considered among the most challenging soil types for agricultural production due to their low content of organic matter and essential nutrients, as well as their poor water-holding capacity. In addition, they are characterized by high evaporation rates and low cation exchange capacity (CEC). Sandy soils also possess a coarse texture and high porosity, which lead to rapid losses of water and nutrients through leaching. This negatively affects plant growth and productivity, particularly leafy vegetable crops that require a continuous supply of moisture and nutrients. Therefore, improving the physical and chemical properties of sandy soils has become an essential requirement for enhancing agricultural production efficiency and achieving agricultural sustainability in arid environments [26 , 37].

Organic fertilizers, particularly poultry manure, are considered among the most important agricultural amendments used to improve soil properties and enhance soil fertility due to their high content of organic matter and essential macro- and micronutrients required for plant growth. They contribute to improving soil structure, increasing water-holding capacity, enhancing biological activity and microbial efficiency, as well as increasing nutrient availability and reducing nutrient losses through leaching. These effects are positively reflected in the vegetative and physiological growth of plants cultivated in sandy soils.Furthermore, the application of organic fertilizers improves soil aeration and reduces soil bulk density, which enhances root growth and increases the efficiency of water and nutrient uptake, thereby improving the growth and productivity of agricultural crops in general [36 , 21].

Biochar is considered one of the modern soil amendments of great importance in improving soil properties. It is produced through the pyrolysis of organic residues under limited oxygen conditions and is characterized by high porosity and a large surface area, which enable it to retain water and nutrients and reduce their losses through leaching. Biochar also contributes to improving soil structure, enhancing microbial activity, increasing cation exchange capacity, and reducing soil bulk density, thereby improving the root environment of plants.Numerous studies have indicated that the addition of biochar to sandy soils increases soil moisture content, improves hydrological properties, and enhances water use efficiency, in addition to its role in promoting vegetative growth, productivity, and physiological performance of plants [5 , 9]. Furthermore, studies have demonstrated that biochar produced from palm residues can improve soil porosity and water retention and increase microbial activity in the soil, which is positively reflected in soil fertility and agricultural sustainability [26 , 30].

Superabsorbent polymers, including potassium polyacrylate, are considered among the modern technologies used to improve water use efficiency in agriculture, owing to their high capacity to absorb, retain, and gradually release water according to plant requirements. These materials are characterized by a three-dimensional network structure containing hydrophilic functional groups that enable them to store large amounts of moisture within the soil, thereby reducing water losses through evaporation or leaching and improving moisture stability in the root zone.These polymers also contribute to improving the physical properties of soil, increasing soil porosity, and reducing water stress on plants, particularly under arid and semi-arid conditions. Recent studies have demonstrated that the use of potassium polyacrylate improved soil moisture, enhanced water use efficiency, and improved certain growth and yield characteristics in several agricultural crops. In addition, it plays an important role in reducing nutrient losses and improving the water environment surrounding plant roots[10 ,27].

Despite the significant importance of poultry manure, biochar, and potassium polyacrylate in improving soil properties and enhancing plant growth, studies concerning the interactive effects among these treatments in sandy soils are still limited, particularly with regard to rocket crop cultivation. Therefore, the importance of the present study lies in evaluating the individual and combined effects of poultry manure, biochar, and potassium polyacrylate on certain physiological characteristics of rocket plants grown in sandy soil, with the aim of identifying the most effective treatment for improving soil water retention, enhancing plant water status and soil fertility, and consequently improving plant growth within sustainable agricultural systems.

2- Material and Methods

2-1 Location of the experiment:

The soil samples were sent to the laboratories of the Soil Department, Directorate of Agriculture of Diyala, for physical and chemical analyses and soil texture determination. The results indicated that the experimental soil had a sandy texture, as presented in Table (1). In addition, the initial physicochemical properties of the soil before the application of amendments were determined and are presented in Table (2). The soil was characterized by a pH of 7.39, electrical conductivity (EC) of 2.30 dS m^{-1}, field capacity (FC) of 8.00%, organic matter (OM) content of 1.18%, available nitrogen of 66.57 mg kg^{-1} soil, available phosphorus of 10.27 mg kg^{-1} soil, and available potassium of 180.60 mg kg^{-1} soil. These properties provide important baseline information for interpreting the response of rocket plants and soil characteristics to potassium polyacrylate, biochar, and organic fertilizer treatments.

Table (1): Study Soil Texture .

Loam	Sand	Clay	Soil Texture
4.48 %	92.4 %	3.12 %	
Sandy Soil			

2-2 Experimental Design :

The factorial experiment was conducted according to a Randomized Complete Block Design (RCBD) with three factors. The first factor consisted of poultry manure at two levels (0 and 10 t ha^{-1}), the second factor included potassium polyacrylate at three concentrations (0, 50, and 100 kg ha^{-1}), while the third factor involved biochar at three concentrations (0, 10, and 20 t ha^{-1}).The experiment included 18 treatment combinations with three replicates, resulting in a total of 54 experimental units.

2-3 Experimental Transactions :

Plastic pots (90 × 30 × 30 cm) were filled with approximately 40 kg of soil after being sieved through a 1 mm mesh sieve. The soil was then

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mixed with diammonium phosphate (DAP) fertilizer containing 46% P_2O_5 and 18% N at a rate of 100 kg ha^{-1}, in addition to the application of potassium polyacrylate, biochar, and poultry manure at the specified levels according to the experimental design. Phosphoric acid (85%) was added to the pots at a concentration of 2 mL L^{-1} to reduce soil alkalinity. Rocket seeds were sown on 3/9/2024 at a rate of three seeds per hill and later thinned to one plant per hill. Each pot contained four hills spaced 20 cm apart and 15 cm from the pot edges. The pots were randomly distributed within three blocks and covered with shading netting. Urea fertilizer was applied 15 days after germination at a rate of 16 kg ha^{-1} as a uniform supplemental nitrogen application to all experimental units in order to avoid nitrogen deficiency during the vegetative growth stage. Diammonium phosphate (DAP) fertilizer was also incorporated before planting to provide phosphorus and part of the nitrogen requirement. Therefore, mineral fertilization was standardized for all treatments, and the study focused on evaluating the effects of potassium polyacrylate, biochar, and poultry manure.

2-4 Preparation of biochar :

Biochar was prepared locally using a 30-L metal container modified to minimize oxygen entry during the pyrolysis process. The lower opening was tightly sealed, while the upper opening was fitted with a valve allowing only gas release. Palm frond residues were collected, cut into small pieces, placed inside the container, and gradually heated to 400°C for approximately three hours or until smoke emission ceased, indicating the completion of biochar formation. After cooling, the produced biochar was ground and sieved through a 1 mm mesh sieve to obtain a uniform particle size. A sample of the biochar was then sent to the laboratories of the College of Science, University of Kufa, for physical, chemical, and diagnostic analyses.

2-5 Studied Characteristics:

2-5-1 Estimation of Relative Leaf Water Content (%)

The relative water content of the leaves (RWC) was measured according to the method of [38]. Fresh leaves were weighed to obtain their fresh weight (FW), then soaked in distilled water for two hours at 25°C to obtain their saturated weight (TW), and subsequently dried at 65°C for 48 hours until a constant weight was reached to obtain their dry weight (DW). The relative water content of the leaves was calculated using the following equation:

$$RWC (\%) = [(FW - DW) \div (TW - DW)] \times 100$$

2-5-2 Determination of Leaf Nitrogen Content(%)

The nitrogen content of plant leaves was determined using the Kjeldahl method according to [41]. 0.5 g of dry plant material was digested using 5 mL of concentrated sulfuric acid (H_2SO_4) with a mixture of potassium sulfate and copper sulfate as digestion catalysts. The samples were heated until the solution became clear with a light blue tint, indicating complete digestion and conversion of nitrogen to ammonium ions. The mixture was then distilled with 40% sodium hydroxide (NaOH) to release ammonia gas, which was collected in boric acid solution (H_3BO_3). The solution was then pneumaticated with 0.1 N standard hydrochloric acid (HCl), and the nitrogen content was calculated using the standard equation for the Kjeldahl method.

2-5-3 Determination of Leaf Phosphorus Content (%)

The leaf phosphorus content was determined according to [12]. 0.5 g of dry plant material was digested using 5 mL of concentrated sulfuric acid (H_2SO_4) and 2 mL of perchloric acid ($HClO_4$) until a clear solution was obtained. After digestion, the phosphorus content was determined by colorimetric analysis using ammonium molybdate and ascorbic acid. The light absorption was then measured using a spectrophotometer at a wavelength of 700 nm, and the concentration was calculated based on a standard curve for known phosphorus concentrations.

2-5-4 Estimation of Leaf Potassium Content (%)

The leaf potassium content (%) was estimated after digesting 1 g of dry plant material with nitric acid (HNO_3) or perchloric acid ($HClO_4$), then diluting the volume to 100 mL with distilled water. The potassium concentration was measured using atomic absorption spectrometry (AAS) after preparing a standard curve using potassium chloride (KCl) solutions. The percentage of potassium was then calculated based on the measured concentration, dilution volume, and weight of the dry sample [25].

2-6 Statistical Analysis :

The data were statistically analyzed using analysis of variance (ANOVA) in a completely randomized block design (R.C.B.D.). Means were compared using Duncan's multiple range test (DMRT) at the 0.05 level using SPSS software. A t-test was also used to compare the physical and chemical properties of the soil before and after the addition of the amendments.

3- Results and discussion

3-1 Results of Biochar Analyses

3-1-1 Characterization by Field Emission Scanning Electron Microscopy (FE-SEM)

The images presented in Figure (1), obtained using Field Emission Scanning Electron Microscopy (FE-SEM), revealed that the biochar sample produced at 400°C possessed an irregular surface structure characterized by pores, cavities, and longitudinal channels of varying sizes resulting from the decomposition of organic components and the release of volatile compounds during the carbonization process [15]. The images also demonstrated the presence of surface cracks and partial separations attributed to thermal shrinkage and moisture loss. Moderate temperatures such as 400°C contribute to the development of porosity while maintaining structural stability compared with higher temperatures, as reported by [42]. In addition, surface accumulations were observed, which were likely residues of ash or mineral materials that contribute to increasing the active sites for nutrient adsorption and improving cation exchange capacity. These properties enhance the ability of biochar to retain water and nutrients, improve soil aeration, and promote plant growth [6].

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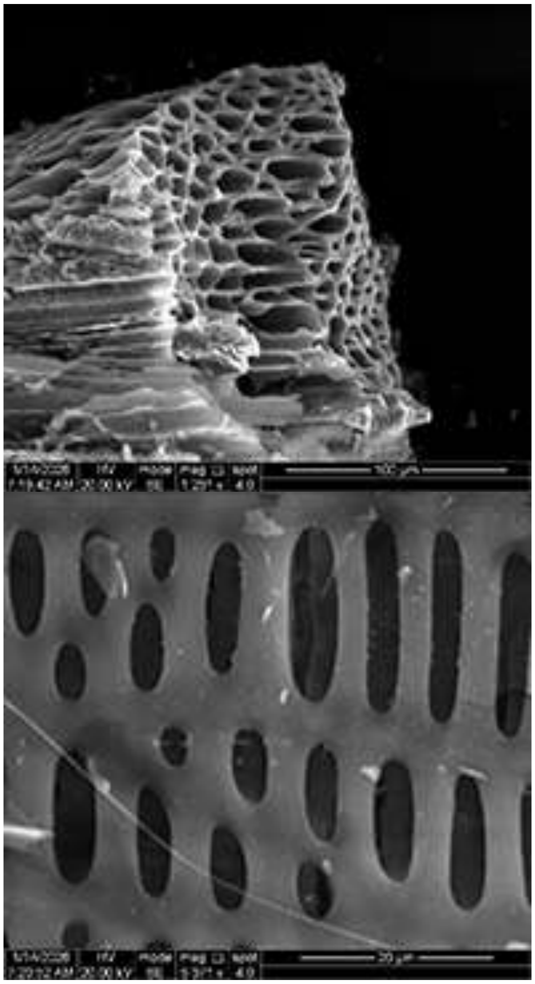

Figure (1): FE-SEM images of biochar.

3-1-2 Characterization by Fourier Transform Infrared Spectroscopy (FT-IR)

Fourier Transform Infrared Spectroscopy (FT-IR) represents an important tool for identifying functional groups and chemical bonds in biochar, as it provides information about the surface characteristics and chemical structure of the material and its role in adsorption, ion exchange, and soil improvement. It also assists in explaining the structural changes resulting from the carbonization process and the efficiency of biochar in agricultural and environmental applications. The results presented in Figure (2) showed peaks at 2923.20 cm^{-1} attributed to aliphatic C–H bonds and at 2310.72 cm^{-1} corresponding to the absorption of carbon dioxide within the pores, indicating the persistence of some incompletely decomposed organic compounds [33]. The peak observed at 1589.34 cm^{-1} represented aromatic C=C functional groups, indicating the formation of stable carbon rings and increased stability of organic matter [16]. The peak at 1417.68 cm^{-1} reflected the presence of polar functional groups such as phenolic and carboxylate groups, which contribute to increasing cation exchange capacity and nutrient retention [33]. Meanwhile, the peaks at 750.31 and 813.96 cm^{-1} indicated aromatic C–H groups, whereas the peaks below 500 cm^{-1} were attributed to mineral bonds such as Si–O and Fe–O resulting from plant ash residues [22].The presence of these functional groups together with the aromatic carbon structure indicates that the produced biochar possesses structural stability and active surface sites that improve soil properties and enhance nutrient retention.

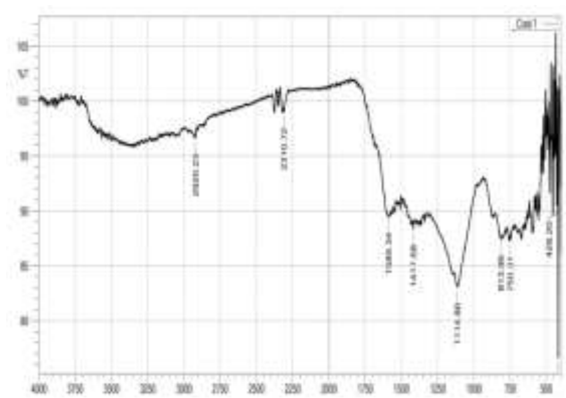

Figure (2): Fourier Transform Infrared (FT-IR) spectrum of biochar surfaces.

3-1-3 Characterization by Energy Dispersive X-ray Spectroscopy (EDS)

The Energy Dispersive X-ray Spectroscopy (EDS) spectrum shown in Figure (3) revealed

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the predominance of carbon at 80.36%, followed by oxygen at 17.86%, along with the presence of minor mineral elements at low concentrations, including calcium (0.76%), potassium (0.70%), magnesium (0.17%), and sodium (0.12%), in addition to trace amounts of iron, manganese, copper, and zinc. This composition is characteristic of biochar produced through the pyrolysis of plant materials, where the loss of volatile compounds leads to an increase in carbon concentration, a higher degree of carbonization, and enhanced chemical stability [35]. The high oxygen content also indicates the presence of oxidized functional groups responsible for adsorption, cation exchange, and nutrient binding [40]. Meanwhile, the mineral elements represent residues of plant ash that contribute to improving soil fertility and are associated with the raw material composition and pyrolysis temperature [13] In general, the predominance of carbon together with the retention of mineral elements confirms the quality of the produced biochar and its suitability for improving the properties of agricultural soils.

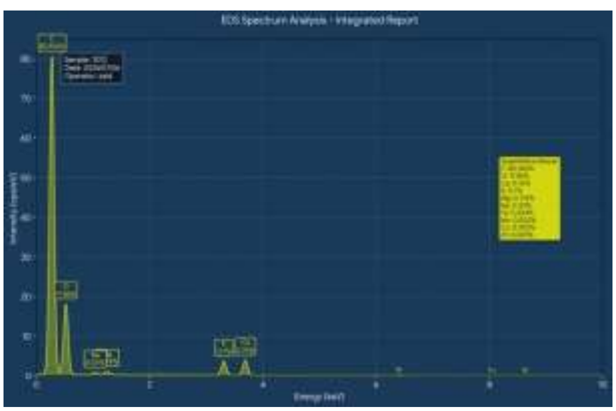

Figure (3): Energy Dispersive X-ray (EDS) spectrum of the biochar sample.

3-2 Effect of Potassium Polyacrylate, Biochar, and Organic Fertilizer Treatments on the Chemical and Physical Properties of the Experimental Soil

The results of the T-test presented in Table (2) indicated significant changes in most soil properties following the application of the amendments, reflecting their role in improving the chemical and physical characteristics of the soil. The mean soil pH increased significantly from 7.39 to 7.53 ($P = 0.015$), which may be attributed to the presence of alkaline compounds in the amendments that contribute to modifying soil acidity [1]. Electrical conductivity (EC) increased from 2.30 to 2.57 dS m^{-1} without significant differences ($P = 0.214$), indicating that the amendments improved soil properties without causing harmful increases in salinity [3]. In addition, field capacity (FC) increased significantly from 8.00% to 13.93% ($P = 0.000$) as a result of improved soil structure and enhanced water-holding capacity [16]. Organic matter (OM) content also increased from 1.18 to 1.46 g kg^{-1} soil ($P = 0.000$), owing to the richness of the amendments in organic materials and their positive role in improving soil fertility [32]. Furthermore, the soil recorded significant increases in nitrogen content from 66.57 to 74.53 mg kg^{-1} soil, phosphorus from 10.27 to 11.64 mg kg^{-1} soil, and potassium from 180.60 to 188.95 mg kg^{-1} soil at probability levels of 0.001, 0.002, and 0.000, respectively. These results indicate the effectiveness of the amendments in increasing nutrient availability and improving soil fertility, thereby confirming their efficiency as sustainable approaches for enhancing soil quality and productivity [39].

Table (2) : T-test analysis of the physical and chemical properties of the experimental soil before and after treatment with soil amendments.

3-3 Effect of Organic Fertilizer, Potassium Polyacrylate, and Biochar Treatments on the Physiological Characteristics of Rocket Plants

3-3-1 Relative Water Content (RWC) (%)

The results presented in Table (3) indicated highly significant differences at the 5% level in relative water content (%) as affected by the application of organic fertilizer to rocket plants at a rate of 10 t ha^{-1} compared with the untreated control. The treatment of 10 t ha^{-1} recorded the highest mean value of 94.08%, representing an increase of 14.36% compared with the control treatment, which recorded 82.26%. The increase in relative water content (RWC) may be attributed to the role of organic fertilizer in improving soil properties, increasing water-holding capacity, and enhancing soil structure and aeration. These effects promote water and nutrient uptake, improve cellular water balance, and reduce water stress, which are positively reflected in the physiological status of the plant and water use efficiency [4]. It should be noted that all experimental units were irrigated using the same water source and irrigation schedule throughout the experimental period. Therefore, the observed differences in relative water content can be mainly attributed to the effects of the applied treatments on soil water retention and plant water uptake efficiency rather than differences in irrigation conditions.

The results presented in Table (3) also indicated highly significant differences at the 5% level in relative water content (%) as a result of treating rocket plants with potassium polyacrylate at concentrations of 0, 50, and 100 kg ha^{-1}. The concentration of 100 kg ha^{-1} recorded the highest mean value of 109.1%, representing an increase of 66.00% compared with the control treatment, which recorded 65.72%. The increase in RWC may be attributed

P-value	T-Value	SD	Mean		Trait
0.015	-8.126	0.08718	7.3900	B	pH
		0.05774	7.5333	A	
0.214	-1.800	0.02082	2.3033	B	EC dS m^{-1}
		0.25482	2.5733	A	
0.000	-178.00	0.00000	8.0000	B	FC %
		0.05774	13.9333	A	
0.000	-83.000	0.00000	1.1800	B	OM %
		0.00577	1.4567	A	
0.001	-36.447	0.32146	66.5667	B	N %
		0.11547	74.5333	A	
0.002	-20.424	0.06083	10.2700	B	P %
		0.05508	11.6367	A	
0.000	-51.951	0.26458	180.600	B	K %
		0.05000	188.950	A	

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to the ability of superabsorbent polymers to store water and nutrients and gradually release them within the root zone, thereby reducing fluctuations in soil moisture and improving the efficiency of water and nutrient use. This is reflected in improved cellular turgidity, maintenance of membrane integrity, and increased relative water content even under water stress conditions [23 , 34] which is consistent with the findings of [19].

The results also indicated highly significant differences in relative water content as affected by the application of biochar to rocket plants at rates of 0, 10, and 20 t ha^{-1}. The treatment of 20 t ha^{-1} recorded the highest mean value of 100.9%, representing an increase of 33.85% compared with the control treatment, which recorded 75.38%. The increase in relative water content may be attributed to the porous structure and large surface area of biochar, which enhance its ability to absorb, retain, and gradually release water to plants. This increases water availability within the root zone, improves soil moisture retention, and reduces water losses through evaporation or leaching [8] .Moreover, biochar contributes to improving soil structure and aeration and promotes root growth, which was reflected in the increase in root system dry weight shown in Table (3). This, in turn, enhanced the efficiency of water and nutrient uptake and supported the physiological status of the plant [8].

The results further demonstrated highly significant differences at the 5% level in relative water content due to the binary interactions among organic fertilizer, biochar, and polymer treatments. The combination of 100 kg ha^{-1} polymer + 20 t ha^{-1} biochar recorded the highest mean value of 141.8%, representing an increase of 107.25% compared with the lowest mean value of 60.00% obtained under the untreated control. Similarly, the combination of 10 t ha^{-1} organic fertilizer + 20 t ha^{-1} biochar recorded a mean value of 107.5%, with an increase of 53.17% compared with the control treatment, which recorded 70.18%. Meanwhile, the combination of 10 t ha^{-1} organic fertilizer + 100 kg ha^{-1} polymer achieved the highest mean value of 117.1%, representing an increase of 89.32% compared with the lowest mean value of 61.85%. The results presented in Table (3) also indicated highly significant differences in relative water content due to the triple interaction among organic fertilizer, biochar, and polymer treatments. The combination of 10 t ha^{-1} organic fertilizer + 100 kg ha^{-1} polymer + 20 t ha^{-1} biochar recorded the highest mean value of 141.8%, representing an increase of 136.33% compared with the lowest mean value of 60.00% observed under the untreated control. This treatment did not differ significantly from the combination of 0 organic fertilizer + 0 polymer + 10 t ha^{-1} biochar, which recorded 61.29%, as shown in Table (3).

Table (3): Effect of organic fertilizer, polymer, and biochar application on relative water content (%).

The dual interaction between organic fertilizer and polymer	biochar			polymer	organic fertilizer
	20	10	0		
61.85 f	64.27	61.29	60.00	0	0

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	m	n	n		
83.82 d	95.66 f	83.74 h	72.06 k	50	
101.1 b	123.2 b	101.6 e	78.49 j	100	
69.59 e	71.83 k	69.10 l	67.85 l	0	10
95.55 bc	109.0 d	95.51 f	82.08 i	50	
117.1 a	141.8 a	117.6 c	91.82 g	100	
88.14	100.9 a	88.15 b	75.38 c	Average impact of biochar	
The dual interaction between organic fertilizer and biochar					
Average effect of organic fertilizer	biochar concentrate			Organic fertilizer concentration	
	20	10	0		
82.26 b	94.39 ab	82.22 bc	70.18 c	0	
94.08 a	107.5 a	94.08 ab	80.58 bc	10	
The dual interaction between polymer and biochar					
Average polymer effect	biochar concentrate			Polymer concentrations	
	20	10	0		
65.72 c	68.05 e	65.20 e	63.93 e	0	
89.69 b	102.3 b	89.63 c	77.07 d	50	
109.1 a	132.5 a	109.6 b	85.15 c	100	

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3-3-2 Leaf Nitrogen Content (%)

The results presented in Table (4) indicated highly significant differences at the 5% level in leaf nitrogen content (%) as affected by the application of organic fertilizer to rocket plants at a rate of 10 t ha^{-1} compared with the untreated control. The treatment recorded the highest mean value of 0.991%, representing an increase of 44.46% compared with the control treatment, which recorded 0.686%. The increase in nitrogen content may be attributed to the role of organic fertilizer in improving the availability of this nutrient in the soil, as nitrogen is gradually released through microbial activity and decomposition and mineralization processes, thereby providing a continuous source for plant uptake during the growth period [18]. These findings are consistent with the study of [20] on lettuce plants, which demonstrated that the application of poultry manure at a concentration of 15% increased nitrogen content to 2.648% compared with the control treatment, which recorded 1.376%.

The results presented in Table (4) indicated highly significant differences at the 5% level in leaf nitrogen content (%) as affected by the application of potassium polyacrylate to rocket plants at concentrations of 0, 50, and 100 kg ha^{-1}. The concentration of 100 kg ha^{-1} recorded the highest mean value of 1.143%, representing an increase of 110.11% compared with the control treatment, which recorded 0.544%. The increase in nitrogen content may be attributed to the ability of potassium polyacrylate to retain water and gradually release it within the root zone, thereby reducing nutrient losses through leaching and maintaining nitrogen availability in the forms of nitrate and ammonium for a longer period. Consequently, nitrogen uptake and utilization efficiency are enhanced, in addition to the role of the polymer in the gradual release of nutrients and the promotion of plant growth [28].

The results presented in Table (4) also indicated highly significant differences in leaf nitrogen content as affected by the application of biochar to rocket plants at rates of 0, 10, and 20 t ha^{-1}. The treatment of 20 t ha^{-1} recorded the highest mean value of 0.977%, representing an increase of 46.03% compared with the control treatment, which recorded 0.669%. The increase in nitrogen content may be attributed to the role of biochar in improving soil properties, as its high porosity and large surface area enhance the retention of nitrogenous compounds and reduce their losses through leaching or volatilization. This increases nitrogen availability and uptake by plants [14].

The results presented in Table (4) also indicated highly significant differences at the 5% level in leaf nitrogen content due to the binary and triple interactions among the treatments. Among the binary interactions, the combination of 100 kg ha^{-1} polymer + 20 t ha^{-1} biochar recorded the highest mean value of 1.385%, representing an increase of 167.37%. This was followed by the combination of 10 t ha^{-1} organic fertilizer + 100 kg ha^{-1} polymer, which recorded a mean value of 1.302% with an increase of 149.90%, and then the combination of 10 t ha^{-1} organic fertilizer + 20 t ha^{-1} biochar, which achieved a mean value of 1.170% with an increase of 101.03%. In contrast, the untreated control treatments recorded the lowest mean values, ranging from 0.518% to 0.582%, without significant differences among them.Regarding the triple interaction, the combination of 10 t ha^{-1} organic fertilizer + 100 kg ha^{-1} polymer + 20 t ha^{-1} biochar achieved the highest mean value of 1.537%, representing an increase of 204.35% compared with the lowest mean value of 0.505% recorded under the untreated control treatment.

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Table (4): Effect of organic fertilizer, polymer, and biochar application on leaf nitrogen content (%).

The dual interaction between organic fertilizer and polymer	biochar			Polymer	organic fertilizer
	20	10	0		
0.521 c	0.544 n	0.515 q	0.505 r	0	0
0.551 c	0.575 k	0.554 m	0.525 p	50	
b 0.985	1.233 d	1.008 f	0.715 i	100	
c 0.567	0.605 j	0.565 l	0.531 o	0	10
b 1.104	1.368 c	1.123 e	0.823 h	50	
a1.302	1.537 a	1.454 b	0.915 g	100	
0.838	a 0.977	b0.8698	0.669 c	Average impact of biochar	
The dual interaction between organic fertilizer and biochar					
Average effect of organic fertilizer	biochar concentrate			Organic fertilizer concentration	
	20	10	0		
0.686 b	0.784 bc	0.692 c	0.582 c	0	
a 0.991	1.170 a	1.047 ab	0.756 bc	10	
The dual interaction between polymer and biochar					
Average polymer effect	Biochar concentrations			Polymer concentrations	
	20	10	0		
c 0.544	0.574 cde	0.54 de	0.518 e	0	
b0.828	0.971 b	0.839 bc	0.674 cde	50	
a 1.143	1.385 a	1.231 a	0.815 bcd	100	

3-3-3 Leaf Phosphorus Content (%)

The results presented in Table (5) indicated highly significant differences at the 5% level in leaf phosphorus content (%) as affected by the

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application of organic fertilizer to rocket plants at a rate of 10 t ha^{-1} compared with the untreated control. The treatment recorded the highest mean value of 0.125%, representing an increase of 40.44% compared with the control treatment, which recorded 0.089%. The increase in phosphorus content may be attributed to the role of organic matter in enhancing phosphorus availability in the soil. The decomposition of organic matter releases organic acids that reduce phosphorus fixation and convert it into more available forms for plant uptake, in addition to the role of microbial activity in the mineralization of organic phosphorus [2]. These findings are consistent with the study of [20] on lettuce plants, which reported an increase in phosphorus content to 0.265% compared with the control treatment, which recorded 0.155%.

The results presented in the same table also indicated highly significant differences at the 5% level in leaf phosphorus content (%) as affected by the application of potassium polyacrylate to rocket plants at concentrations of 0, 50, and 100 kg ha^{-1}. The concentration of 100 kg ha^{-1} recorded the highest mean value of 0.141%, representing an increase of 93.15% compared with the control treatment, which recorded 0.073%. The increase in phosphorus concentration may be attributed to the role of superabsorbent polymers in improving soil moisture and enhancing phosphorus solubility and mobility toward plant roots. In addition, these polymers reduce water stress, promote root growth and nutrient uptake efficiency, and stimulate phosphorus-solubilizing microorganisms that convert phosphorus into more available forms, thereby enhancing its accumulation in plant tissues [28].

The results presented in Table (5) demonstrated highly significant differences in leaf phosphorus content as affected by the application of biochar to rocket plants at rates of 0, 10, and 20 t ha^{-1}. The treatment of 20 t ha^{-1} recorded the highest mean value of 0.123%, representing an increase of 38.20% compared with the control treatment, which recorded 0.089%. The increase in phosphorus content may be attributed to the role of biochar in reducing phosphorus fixation and improving the chemical properties of soil, as well as increasing cation exchange capacity and organic matter content, which enhance phosphorus availability and uptake by plants [8]. Moreover, the high porosity of biochar provides a favorable environment for phosphate-solubilizing microorganisms. In addition, biochar contains certain amounts of phosphorus within its mineral components, which positively affects plant growth and productivity [11].

The results presented in the same table also revealed highly significant differences at the 5% level in leaf phosphorus content due to the binary interactions among organic fertilizer, biochar, and polymer treatments. The combination of 100 kg ha^{-1} polymer + 20 t ha^{-1} biochar recorded the highest mean value of 0.158%, representing an increase of 163.33% compared with the lowest mean value of 0.060% observed under the untreated control. Similarly, the combination of 10 t ha^{-1} organic fertilizer + 20 t ha^{-1} biochar recorded a mean value of 0.143%, representing an increase of 88.15% compared with the lowest mean value of 0.076%. Meanwhile, the combination of 10 t ha^{-1} organic fertilizer + 100 kg ha^{-1} polymer achieved the highest mean value of 0.155%, representing an increase of 150% compared with the lowest mean value of 0.062%.The results shown in Table (5) also indicated highly significant differences in leaf phosphorus content due to the triple interaction among organic fertilizer, biochar, and polymer treatments. The combination of 10 t ha^{-1} organic fertilizer + 100 kg ha^{-1} polymer + 20 t ha^{-1} biochar recorded the highest mean value of 0.175%, representing an increase of 204.35% compared with the lowest mean value of 0.052% recorded under the untreated control treatment.

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Table (5): Effect of organic fertilizer, polymer, and biochar application on leaf phosphorus content (%).

The dual interaction between organic fertilizer and polymer	biochar			polymer	organic fertilizer
	20	10	0		
0.062 d	0.076 n	0.058 q	0.052 r	0	0
0.078 c	0.093 k	0.079 m	0.064 p	50	
0.127 b	0.142 d	0.129 f	0.112 i	100	
0.084 c	0.102 j	0.083 l	0.069 o	0	10
0.135 b	0.153 c	0.136 e	0.116 h	50	
0.155 a	0.175 a	0.168 b	0.122 g	100	
0.106	0.123 a	0.109 b	0.089 c	Average impact of biochar	
The dual interaction between organic fertilizer and biochar					
Average effect of organic fertilizer	biochar concentrate			Organic fertilizer concentration	
	20	10	0		
0.089 b	0.103 bc	0.088 c	0.076 c	0	
0.125 a	0.143 a	0.129 ab	0.102 bc	10	
The dual interaction between polymer and biochar					
Average polymer effect	Biochar concentrations			Polymer concentrations	
	20	10	0		
0.073 c	0.089 ef	0.070 fg	0.060 g	0	
0.107 b	0.123 bc	0.108 cde	0.090 def	50	
0.141 a	0.158 a	0.148 ab	0.117 cd	100	

3-3-4 Leaf Potassium Content (%)

The results presented in Table (6) indicated highly significant differences at the 5% level in leaf potassium content (%) as affected by the

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application of organic fertilizer to rocket plants at a rate of 10 t ha^{-1} compared with the untreated control. The treatment recorded the highest mean value of 1.236%, representing an increase of 40.44% compared with the control treatment, which recorded 0.875%. The increase in potassium content may be attributed to the role of organic matter in improving the availability of this nutrient and reducing its loss through leaching, in addition to enhancing cation exchange capacity and increasing soil retention of potassium, thereby promoting its uptake by plants [29,32]. Furthermore, improvements in microbial activity and soil structure contribute to enhanced root growth and nutrient uptake efficiency [31]. These findings are consistent with the study of [20] on lettuce plants, which reported an increase in potassium content to 1.424% compared with the control treatment, which recorded 1.392%.

The results presented in Table (6) indicated highly significant differences at the 5% level in leaf potassium content (%) as affected by the application of potassium polyacrylate to rocket plants at concentrations of 0, 50, and 100 kg ha^{-1}. The concentration of 100 kg ha^{-1} recorded the highest mean value of 1.368%, representing an increase of 88.17% compared with the control treatment, which recorded 0.727%. The increase in potassium content may be attributed to the cation exchange capacity of potassium polyacrylate resulting from the presence of negatively charged carboxylic groups, which facilitate the adsorption, retention, and gradual release of cations. In addition, the –COOK functional group serves as an additional source of potassium ions that are gradually released as the polymer swells with water, thereby increasing potassium availability and its uptake by plants [24].

The results presented in the same table also demonstrated highly significant differences in leaf potassium content as affected by the application of biochar to rocket plants at rates of 0, 10, and 20 t ha^{-1}. The treatment of 20 t ha^{-1} recorded the highest mean value of 1.245%, representing an increase of 44.59% compared with the control treatment, which recorded 0.861%. The increase in potassium content may be attributed to the presence of this element within the ash fraction of the organic material used for biochar production, as shown in Figure (2). In addition, biochar possesses a high surface area and porosity that enhance cation retention and reduce potassium losses through leaching. Furthermore, biochar improves soil properties, root growth, and nutrient uptake efficiency, which positively influences the physiological processes of the plant [8].

The results presented in the table also indicated highly significant differences at the 5% level in leaf potassium content due to the binary and triple interactions among organic fertilizer, biochar, and polymer treatments. Among the binary interactions, the combination of 100 kg ha^{-1} polymer + 20 t ha^{-1} biochar recorded the highest mean value of 1.492%, representing an increase of 191.97%. This was followed by the combination of 10 t ha^{-1} organic fertilizer + 20 t ha^{-1} biochar, which recorded a mean value of 1.413% with an increase of 102.72%, and then the combination of 10 t ha^{-1} organic fertilizer + 100 kg ha^{-1} polymer, which achieved a mean value of 1.483% with an increase of 180.87% compared with the lowest mean values ranging from 0.511% to 0.697% under the untreated control treatments. Regarding the triple interaction, the combination of 10 t ha^{-1} organic fertilizer + 100 kg ha^{-1} polymer + 20 t ha^{-1} biochar recorded the highest mean value of 1.660%, representing an increase of 367.60% compared with the lowest mean value of 0.355% obtained under the untreated control treatment.

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Table (6): Effect of organic fertilizer, polymer, and biochar application on leaf potassium content (%).

The dual interaction between organic fertilizer and polymer	biochar			polymer	organic fertilizer
	20	10	0		
0.528 d	m0.782	p0.448	0.355 q	0	0
0.842 c	j1.124	l0.839	o0.564	50	
1.253 b	d1.325	f1.262	h1.173	100	
0.925 c	i1.153	k0.955	0.668 n	0	10
1.302 b	c1.427	e1.291	h1.188	50	
1.483 a	0 a1.66	b1.572	g1.216	100	
1.055	1.245 a	1.061 b	0.861 c	Average impact of biochar	
The dual interaction between organic fertilizer and biochar					
Average effect of organic fertilizer	biochar concentrate			Organic fertilizer concentration	
	20	10	0		
0.875 b	1.077 bc	0.849 cd	0.697 d	0	
1.236 a	1.413 a	1.272 ab	1.024 bc	10	
The dual interaction between polymer and biochar					
Average polymer effect	Biochar concentrations			Polymer concentrations	
	20	10	0		
0.727 c	0.967 def	0.701 fg	0.511 g	0	
1.072 b	1.275 abc	1.065 cde	0.876 ef	50	
1.368 a	1.492 a	1.417 ab	1.194 bcd	100	

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Conclusion

The results of the present study indicate that the application of poultry manure, potassium polyacrylate, and biochar led to a clear improvement in the physical and chemical properties of the experimental soil, as significant increases were observed in field capacity, organic matter content, and the availability of essential nutrients. Furthermore, the microscopic and spectroscopic analyses of the biochar produced from palm residues at a pyrolysis temperature of 400°C demonstrated that the biochar possessed a porous structure and active functional groups, resulting in increased carbon stability and enhanced retention of mineral elements. These improvements were positively reflected in the physiological characteristics of the plant, including increased leaf contents of nitrogen (N), phosphorus (P), and potassium (K), as well as improved plant water status. Overall, the findings of this study confirm the efficiency of the applied treatments in enhancing soil fertility and sustainably improving the growth of rocket plants.

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