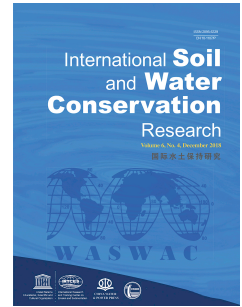


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Two-Year Monitoring of Biochar Effects on Soil and Water Conservation in USLE Plots under Field Conditions

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Two-Year Monitoring of Biochar Effects on Soil and Water Conservation in USLE Plots under Field Conditions

Gilda Moafi^a, Leila Gholami^b, Ataollah Kavian^c, and Hosein Kheirfam^d

a. Ph.D. graduate, Department of Watershed Management Engineering, Faculty of Natural Resources, Sari Agricultural Sciences and Natural Resources University, Sari, Iran. gildamoafi@yahoo.com

b. Associate Professor (corresponding author), Department of Watershed Management Engineering, Faculty of Natural Resources, Sari Agricultural Sciences and Natural Resources University, Sari, Iran. l.gholami@sanru.ac.ir

c. Professor, Department of Watershed Management Engineering, Faculty of Natural Resources, Sari Agricultural Sciences and Natural Resources University, Sari, Iran. a.kavian@sanru.ac.ir

d. Associate Professor, Department of Rangeland and Watershed Management, Faculty of Natural Resources, Urmia University, Urmia, Iran. h.kheirfam@yahoo.com

Biochar production

Populus nigra
branches

Pyrolysis



Biochar applications to USLE plots



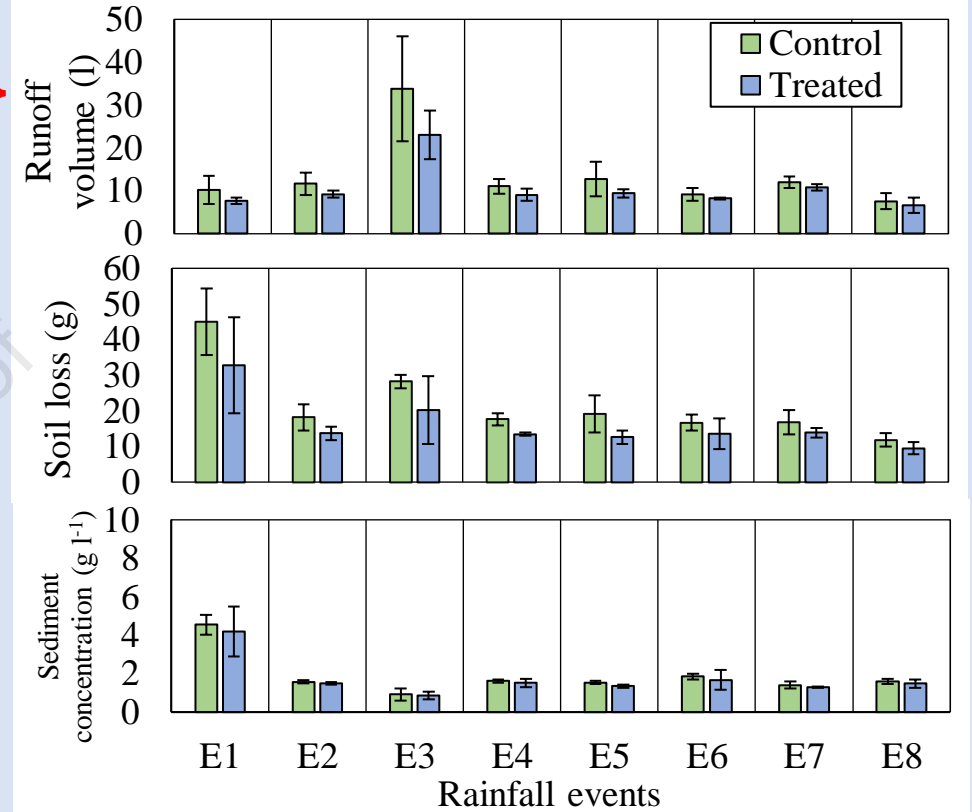
Measurement



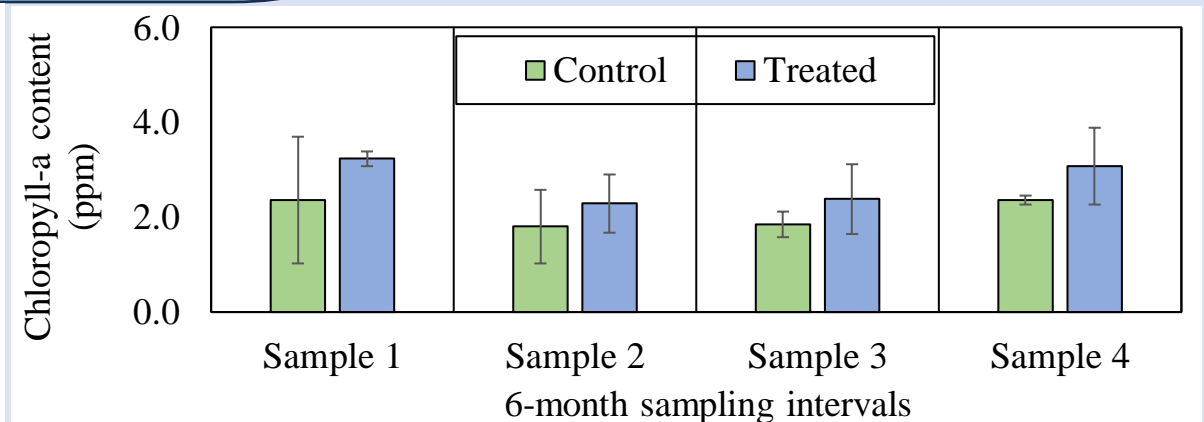
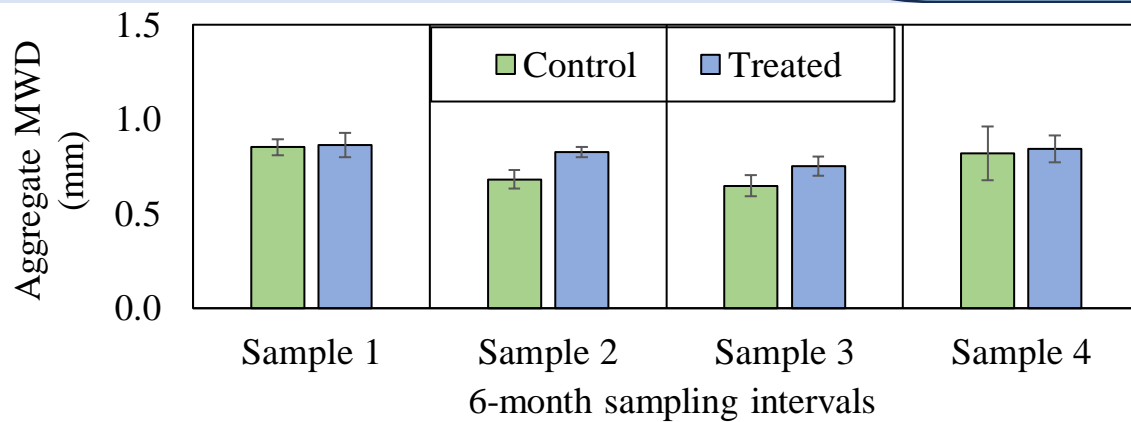
Evaluations of soil properties



Decreasing runoff volume and soil loss



Improving soil properties



1 **Two-Year Monitoring of Biochar Effects on Soil and Water Conservation in** 2 **USLE Plots under Field Conditions**

3 4 **Abstract**

5 Biochar, a carbon-rich material, contributes to sustainable soil and water management by improving soil
6 health, and understanding its behavior and both its short-term and long-term effects on soil is essential.
7 This study investigates the impact of produced biochar from *Populus nigra* branches, applied at 32.5 t
8 ha⁻¹, on runoff, sediment yield, and soil properties in abandoned rainfed plots. Quantitative assessments
9 of runoff and sediment yield following natural rainfall events, coupled with biannual evaluations of soil
10 properties, formed the basis of this investigation. The findings revealed that biochar application in
11 treated plots led to average reductions of 20%, 24%, and 8% in runoff volume, soil loss, and sediment
12 concentration, respectively, compared to control plots. Soil aggregate stability, evaluated through the
13 mean weight diameter (MWD) index, together with soil porosity and soil moisture, showed significant
14 enhancement, with all parameters attaining their maximum values one year after application.
15 Additionally, soil chemical properties, including pH, electrical conductivity (EC), and soil organic
16 carbon (SOC), exhibited substantial improvements, with increases of 4.5, 20.5, and 21%, respectively,
17 relative to control samples. The independent effects of biochar and time on SOC were both significant
18 at the 99% level. Furthermore, the biological index of chlorophyll a (Ch-a) content increased by 31%,
19 with a statistically significant difference in response to biochar at the 95% confidence level. These
20 findings highlight the potential of biochar derived from *Populus nigra* branches as an effective and
21 sustainable strategy for soil and water conservation in abandoned rainfed semi-arid environments.
22 Future research should investigate long-term biochar effects on carbon stability across soils with varying
23 textures and organic matter.

24
25 **Keywords:** Abandoned Rainfed, Organic Amendments, Runoff and Sediment, Natural
26 Rainfall, USLE Plots

27

28 1. Introduction

29 Soil erosion leads to the depletion of fertile topsoil (Kagabo et al., 2013) and contributes
30 to severe environmental consequences (Assouline et al., 2017), posing significant threats to soil
31 health and biodiversity (Qiu et al., 2021). The rate of soil loss is particularly concerning in
32 abandoned rainfed agricultural lands, where the absence of vegetation and the persistence of
33 non-standard tillage practices exacerbate erosion (Cerdeira et al., 2018; Kheirfam et al., 2020). In
34 such areas, effective soil protection strategies must be implemented promptly to mitigate the
35 impact of raindrop kinetic energy and splash erosion (Kheirfam et al., 2017; Gholami et al.,
36 2019). While biological methods for controlling soil erosion are often impractical or infeasible
37 under critical conditions, soil amendments serve as a viable alternative for soil conservation
38 (Adekalu et al., 2007). The usage of organic amendments to improve soil structure and
39 conditions are recognized as an efficient, cost-effective, and multifunctional approach to
40 erosion control (Gholami et al., 2016; Chen et al., 2020). By enhancing soil stability and
41 resilience, these amendments contribute to sustainable land management practices and long-
42 term soil health.

43 Biochar, an organic soil amendment produced through the pyrolysis of diverse biological
44 sources, has garnered increasing attention for its potential in carbon sequestration, enhancing
45 soil fertility, and influencing soil properties (Laird et al., 2010; Gholami et al., 2019, 2022;
46 Acharya et al., 2024). Various materials—including wood, straw mulch, bagasse, vines,
47 molasses, manure, sewage sludge, and paper sludge—serve as feedstocks for biochar
48 production (Gholami et al., 2022). Recent studies have examined the effects of biochar
49 application on runoff volume and sediment yield, with most findings highlighting its efficacy
50 in reducing runoff, minimizing soil loss, and mitigating erosion (Ding et al., 2016; Zhi-gou et
51 al., 2017; Gholami et al., 2019; Yu et al., 2021). Additionally, biochar has demonstrated success
52 in enhancing various soil properties, including:

53 - Soil structure and physical characteristics (Ibrahim et al., 2021; Sun et al., 2021; Park et
54 al., 2023)

55 - Chemical properties, such as nutrient retention and pH balance (Song et al., 2015; Fan et
56 al., 2024; Liu et al., 2024; Zhao et al., 2024)

57 - Organic matter content, contributing to soil fertility (Glaser et al., 2002; Kammann et al.,
58 2011; Wang et al., 2022)

59 - Microbial community dynamics, fostering soil biological activity (Beheshti et al., 2018;
60 Abbas et al., 2019; Ren et al., 2020; Chen et al., 2024b; Moyo et al., 2025)

61 To advancement of large-scale applications, it is essential to evaluate biochar treatments
62 under natural field conditions and compare results with laboratory-based findings. In particular,
63 biochar derived from *Populus nigra* branches requires further investigation to assess its long-
64 term efficacy across diverse soil types and environmental contexts.

65 The study area is located within the Zarinehroud sub-watershed, a part of the larger Urmia
66 Lake watershed in West Azerbaijan Province, Iran. This region has undergone substantial
67 environmental changes due to the development of drainage and irrigation networks, dam
68 construction, and population growth, which have driven land-use transitions from rangelands
69 to rainfed and irrigated agriculture. These shifts have contributed to a decline in soil quality and
70 productivity, leading to an expansion of abandoned rainfed agricultural lands. The resulting
71 erosional landscapes cause both quantitative and qualitative losses of soil and water while
72 introducing significant amounts of sediment and pollutants into Lake Urmia during rainfall
73 events, exacerbating environmental challenges (Kheirfam et al., 2020). Given the ecological
74 significance of Lake Urmia and the importance of studying sediment dynamics and soil
75 degradation, this location was selected for the research project. The experiment was conducted
76 using standard erosion plots based on the Universal Soil Loss Equation (USLE). The most
77 widely used research plot dimensions-originally developed by Duley and Miller (1923) at

78 University of Missouri with dimensions of measure 1.83×1.22 m and designed slope with
79 natural area slope (Alewell et al., 2019). These unit plots served as baseline conditions, enabling
80 comparisons with various influencing factors such as topography, cropping systems, soil
81 management practices, and conservation strategies.

82 This study aims to conserve soil and water resources through the application of organic
83 amendments in field conditions. The research focuses on two primary objectives:

84 1- Assessing the role of biochar in reducing surface runoff and soil loss

85 2- Examining its impact on key physical, chemical, and biological soil properties

86 The experiment was conducted on an abandoned rainfed hillside in northwest Iran, using
87 standard erosion plots under natural rainfall conditions from October 2021 to March 2024. As
88 an uncontrolled field study, it was designed to evaluate the effects of biochar application on
89 runoff and sediment yield, as well as its influence on soil properties, without external
90 interventions.

91

92 **2. Materials and Methods**

93 *2.1 Study area and field plots*

94 The study was conducted in the abandoned rainfed lands upstream of the Noruzlu diversion
95 dam, situated within the Zarinerood sub-watershed, covering an area of approximately 12,000
96 m² within the broader Urmia Lake watershed in West Azarbaijan Province, Iran. The region
97 experiences an average annual precipitation of 254 mm, a mean temperature of 11.4 °C, relative
98 humidity of 62%, and annual evapotranspiration of 1,142 mm. According to the De Martonne
99 climate classification, the area falls within a semi-arid cold climate zone (Kheirfam et al., 2020).

100 Six standard experimental plots were installed using galvanized sheets, following the
101 Universal Soil Loss Equation (USLE) model. Each plot measured 1.83×22.1 m² (Duley and
102 Miller, 1923). The most uniform hill slope in the study area was selected for their placement to

103 ensure consistency in experimental conditions (Gholami et al., 2018). The plots were positioned
104 on a slope with an average gradient of 25–30%, with a one-meter gap between each plot. To
105 further minimize spatial variability, particular attention was given to selecting a
106 geomorphologically uniform hillslope and ensuring consistent slope gradient, soil surface
107 conditions, and land use history across all experimental plots. To facilitate data collection, tanks
108 and pipes were installed at the end of each plot to channel and capture runoff and sediment
109 during rainfall events (Flanagan et al., 2002). Figure 1 provides a detailed illustration of the
110 USLE plot locations.

111

112

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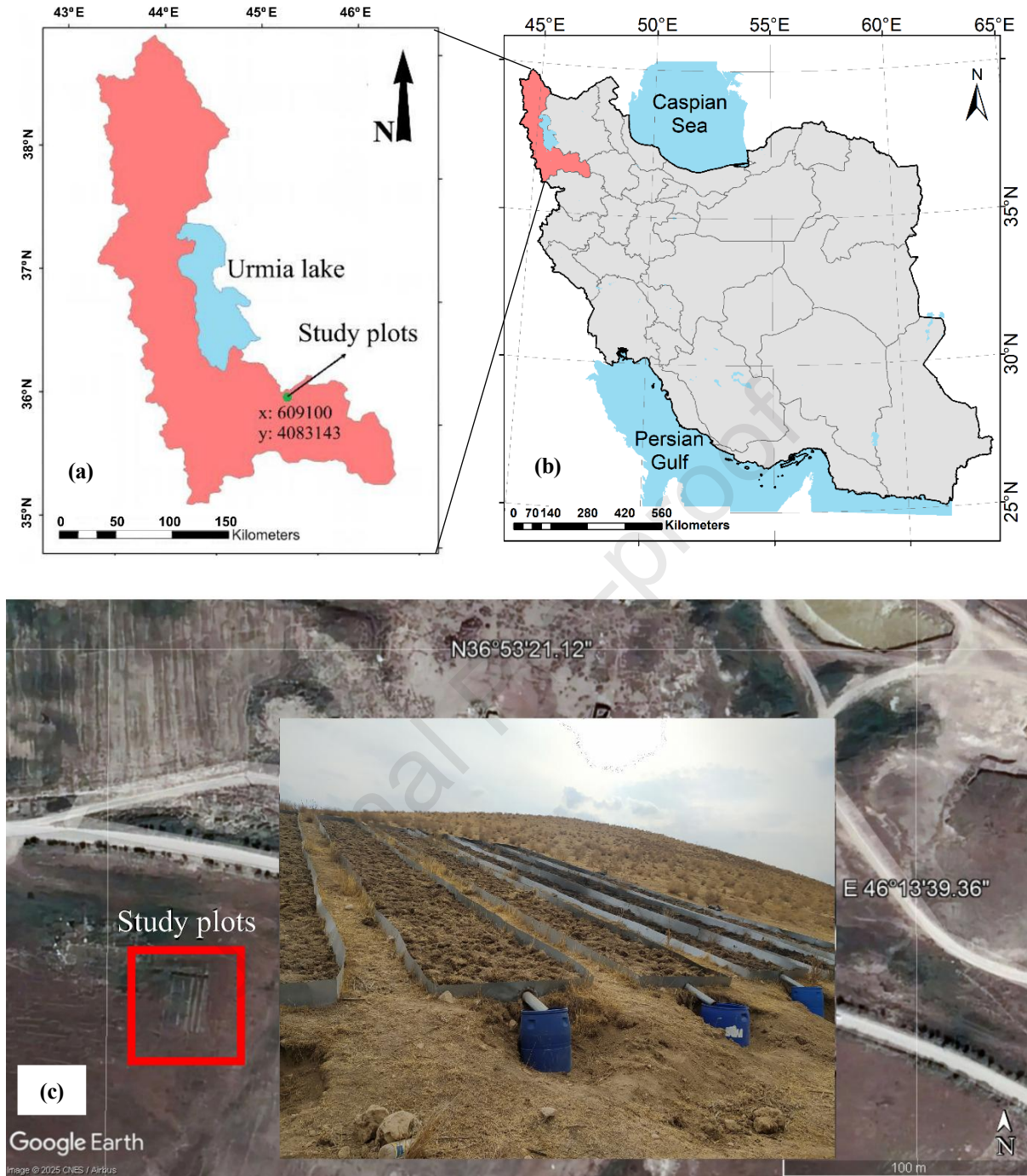
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119 **Figure 1.** The location of the USLE plots in West Azarbaijan province (a) and Iran (b). Google Earth base map
 120 from Google (c), Maxar technologies, accessed April 2025.
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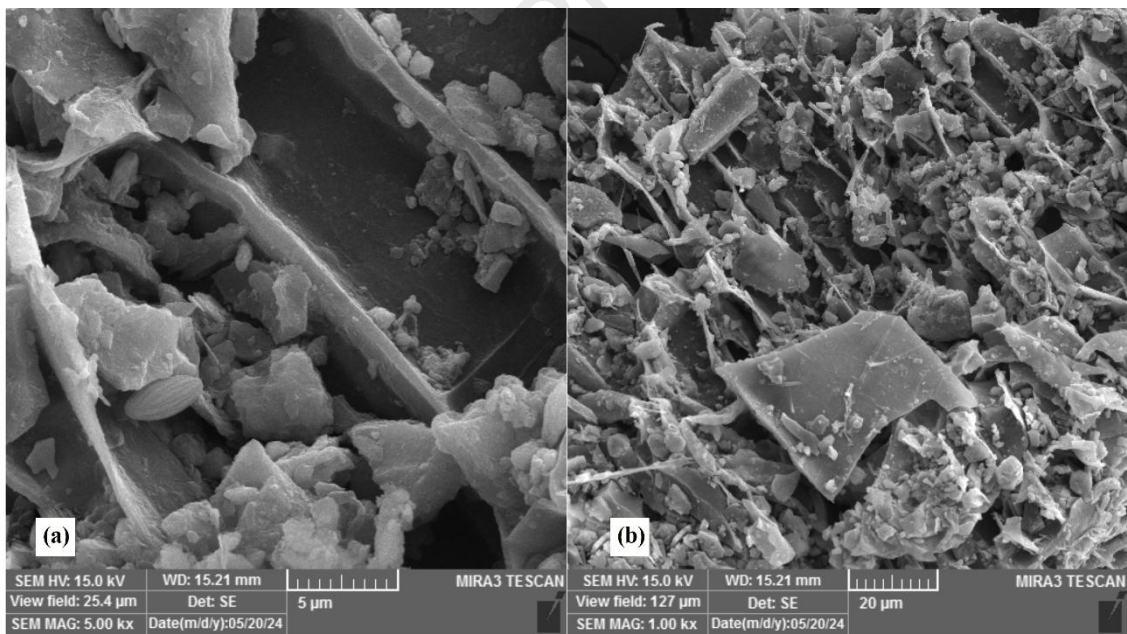
125 2.2 Preparing biochar

126 Biochar was prepared following the identification and collection of wood waste from
127 Tabrizi poplar (*Populus nigra*), which is abundantly available in the northwestern provinces of
128 Iran. The pyrolysis process was carried out at a temperature of 420 °C under minimal oxygen
129 conditions for three hours, resulting in a final product that retained 44% of its original weight
130 (Sadeghi et al., 2016; Gholami et al., 2019). The produced biochar was then sieved through a 2
131 mm mesh to ensure uniform particle size (Peter, 2018). For the experiment, two treatments
132 applied including control (without biochar application) and conservation treatments (with
133 biochar application with the rate of 32.5 t h⁻¹), with each treatment replicated three times (Luo
134 et al., 2017). Following preparation and transportation to the test site, the biochar was evenly
135 distributed on the plot surfaces and incorporated into the soil to a depth of 0-5 cm. Figure 2
136 shows the produced biochar, its application to USLA plots, and the treated plots. Scanning
137 electron microscope (SEM) images of the biochar at two different magnifications are presented
138 in Figure 3. The biochar exhibits an irregular shape with a porous structure (Gholami et al.,
139 2020). Its surface morphology is characterized by honeycomb-like pores, indicative of the
140 carbon skeleton within its structure (Ghani et al., 2013).

141



142
143 **Figure 2.** Running the experiment including produced biochar (a), application to USLA plots (b) and the treated
144 plots (c).
145



146
147 **Figure 3.** The SEM images of *Populus nigra* branches biochar at different magnifications, 5 μ (a) and 20 μ (b).
148

149 2.3 Rainfall events and measurement of runoff and sediment

150 The experiments commenced on October 23, 2021, following the application of biochar to
151 the treated plots. Over the designated study period, eight significant rainfall events resulted in
152 surface runoff. After each event, runoff volume was measured in collection tanks situated at the
153 end of the plots. To analyze sediment content, the collected runoff was first homogenized by

154 stirring, and a 1-liter sample containing both water and sediment was extracted for laboratory
 155 analysis. Sediment measurement was conducted by drying the remaining solids in an oven at
 156 105 °C for 24 hours before weighing (Kukal and Sarkar, 2011; Sadeghi et al., 2015). To quantify
 157 and remove biochar content from the sediment in the conservation treatments, organic matter
 158 was eliminated through combustion at 450 °C for two hours (Hosking, 1938). The sediment
 159 from the control plots was treated identically; therefore, the reported soil loss values for both
 160 treatments are comparable and represent the loss of mineral soil plus any non-biochar soil
 161 organic matter. Table 1 presents meteorological data from the recorded rainfall events. The
 162 characteristics of rainfall events, viz., rainfall height (H), duration (D), average intensity (AI),
 163 and maximum 30-min (I30) intensities, rainfall kinetic energy (KE), and rainfall erosivity index
 164 (EI30), were calculated, based on Wischmeyer and Smith's (1978) method, as presented in Table
 165 2. To understanding quantitative relationships between the runoff volume and soil loss, and the
 166 rainfalls characteristics were calculated R-squared value (R^2) and Pearson correlation (Lu et al.,
 167 2021).

169 **Table 1**
 170 Meteorological information of recorded rainfall events in the present study

Event date	Symbol	Rainfall depth (mm)	Average temperature (°C)	Average humidity (%)	Evaporation (mm)	Snow (cm)	Event date	Symbol	Rainfall depth (mm)	Average temperature (°C)	Average humidity (%)	Evaporation (mm)	Snow (cm)
2022.01.06	E1	12.4	2.1	70.6	0	0	2022.11.27	E5	9.5	9.3	72	1.5	0
2022.01.15	E2	10.9	1.3	77.6	0	0	2023.06.13	E6	11.2	24.1	43.9	7.3	0
2022.03.04	E3	25.9	5.8	56.8	0	0	2024.02.06	E7	11.91	4.1	61.5	0	0
2022.04.30	E4	10.2	17.1	65.8	3.6	0	2024.02.20	E8	7.1	5.2	80.75	0	0

171 **Table 2**
 172 The properties of erosive rainfall events in the study area during the experiment.
 173

Event date	Symbol	H (mm)	D (min)	AI (mm.h ⁻¹)	I30	*KE	**EI30
2022.01.06	E1	12.4	***No data				
2022.01.15	E2	10.9	***No data				
2022.03.04	E3	25.9	1190	1.31	5.4	3.87	20.89
2022.04.30	E4	10.2	490	1.25	4.8	1.57	7.53
2022.11.27	E5	9.5	360	1.58	5.2	1.45	7.54
2023.06.13	E6	11.2	280	2.40	7.6	1.93	14.66
2024.02.06	E7	11.91	720	0.99	4	1.65	6.60
2024.02.20	E8	7.1	620	0.69	1.8	0.88	1.58

174 H (rainfall height), D (rainfall duration), AI (average rainfall intensity), I30 (rainfall maximum 30-min intensity), KE (rainfall
 175 kinetic energy), EI30 (rainfall erosivity index).

176 *KE (for rainfall intensity < 76 mm.h⁻¹) = 0.119 + 0.0873log₁₀ I, and KE (for rainfall intensity > 76 mm.h⁻¹) = 0.283
 177 (Wischmeyer and Smith, 1978).

178 **EI30 = KE × I30 (Wischmeyer and Smith, 1978).

179 *** No high-resolution (10-minute interval) rainfall data were recorded for this event; therefore, event-based rainfall erosivity
 180 indices could not be calculated.

181

182 *2.4 Soil sampling and measurement of soil properties*

183 A comprehensive analysis was conducted to determine soil characteristics. Particle size
 184 distribution was evaluated to classify soil texture (Xue et al., 2019), while total porosity was
 185 calculated following the method outlined by Carter and Gregorich (2007). Soil pH and electrical
 186 conductivity were measured using a HI 9811-5 multimeter. Soil organic carbon content was
 187 determined using the Walkley-Black method (Walkley and Black, 1934), total phosphorus was
 188 quantified via the Olsen method (Olsen and Sommers, 1982), total nitrogen was assessed using
 189 the Kjeldahl method (Kjeldahl, 1883), and basic microbial respiration with the method
 190 proposed by Anderson (1982). Key physical and chemical properties of the soil in the study
 191 area are summarized in Table 3. Images of the tests and sampling of soil analysis in the region
 192 are shown in Figure 4.

193

194 **Table 3**
 195 Soil characteristics in USLE plots

Soil texture	Bulk density (g cm ⁻³)	Total porosity (%)	pH	Electrical conductivity (μs cm ⁻¹)	Organic carbon (%)	Total nitrogen (%)	Total phosphorus (mg kg ⁻¹)	Basic microbial respiration (mg CO ₂ g ⁻¹ day ⁻¹)
Loamy sand	1.04	60	9.2	176.6	0.53	0.31	17.6	0.023

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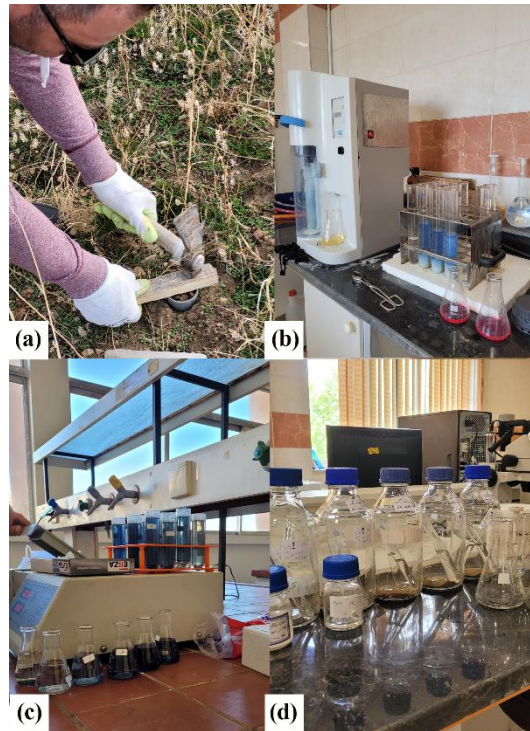


Figure 4. Soil analysis of collected soil from study area, sampling to measurement soil porosity (a), nitrogen measurement (b), phosphorus measurement (c) and measurement of basic microbial respiration (d).

198
199
200
201

202 Soil sampling was conducted to assess changes in soil properties resulting from biochar
203 application. Samples were collected from the surface of both protected and control plots at six-
204 month intervals following treatment, on April 30, 2022, November 29, 2022, May 2, 2023, and
205 December 21, 2023. To ensure representative sampling, soil was collected from multiple points
206 within each plot and mixed to form a composite sample. A portion of the collected soil was air-
207 dried and passed through a four-millimeter sieve, while the remainder was refrigerated at 4 °C
208 for biological analysis (Chamizo et al., 2012). Several key indicators were selected to evaluate
209 changes in soil properties. Aggregate stability was assessed by determining the mean weight
210 diameter (MWD) index using the dry sieving method (Xue et al., 2019). To determine the soil
211 porosity (P), both the bulk density and the particle density must be measured. The bulk density
212 is determined using the cylinder method, while the particle density of the soil is assumed to be
213 2.65 g.m⁻³ (Carter and Gregorich, 2007). The gravimetric soil moisture content (M) was
214 obtained from the difference between the initial and final weights of the soil samples after
215 drying (Kheirfam and Roohi, 2020). Soil pH and electrical conductivity (EC) were measured

216 with a Multimeter HI 9811-5. Soil organic carbon (SOC) content was quantified using the
 217 Walkley-Black method (Walkley and Black, 1934). Additionally, chlorophyll-a (Ch-a) in soil
 218 samples was measured following the method proposed by Ritchie (Ritchie, 2006) and modified
 219 by Castle (Castle et al., 2011). Images of tests to determine soil aggregate stability, pH and EC,
 220 SOC, and Ch-a content are shown in Figure 5.

221



222 **Figure 5.** Investigation of soil changes before and after biochar application by measurement of aggregate mean
 223 weight diameter (MWD) (a), soil pH and electrical conductivity (EC) (b), organic carbon (OC) content (c) and
 224 chlorophyll-a content (d).
 225
 226

227 2.5 Statistical analysis

228 Following the completion of all experiments, a database was compiled to record runoff,
 229 sediment, and soil component data. To facilitate statistical comparisons, data normality was
 230 first assessed (Zahediasl and Ghasemi, 2012) then temporal variations in runoff and sediment
 231 behavior within each treatment were analyzed using a paired t-test (Tabachnick and Fidell,
 232 2013). Additionally, a multivariate analysis of variance (GLM) was conducted to evaluate the

233 effectiveness of biochar treatment and the temporal shifts in soil variables across treatments
 234 (McDonald, 2015). All statistical analyses were performed using SPSS Statistics 27.

235

236 3 Results and Discussion

237 3.1 Effect of biochar on surface runoff, soil loss and sediment concentration

238 The descriptive statistical results, including the mean and standard deviation of runoff
 239 volume, soil loss, and sediment concentration for both the biochar treatment and control, are
 240 presented in Tables 4 and 5.

241

242 **Table 4**
 243 Results of the mean and standard deviation of the runoff volume in control and conservation treatments

Component	Treatment	Variable	Study events							
			E1	E2	E3	E4	E5	E6	E7	E8
Runoff Volume (l)	Control	<i>M</i>	10.17	11.63	33.77	11.03	12.67	9.1	12	7.53
		<i>SD</i>	3.25	2.58	12.26	1.7	4.04	1.49	1.32	1.86
	Biochar	<i>M</i>	7.67	9.2	23	9.07	9.37	8.18	10.83	6.6
		<i>SD</i>	0.76	0.85	5.68	1.44	0.9	0.28	0.76	1.75
Conservation Percent (%)			-24.59	-20.92	-31.89	-17.82	-26.05	-10.07	-9.72	-12.39

244 E1 to E8 are the dates of eight rainfall events during the experiment, including 2022.01.06, 2022.01.15, 2022.03.04, 2022.04.30, 2022.11.27,
 245 2023.06.13, 2024.02.06, and 2024.02.20.

246

247 **Table 5**
 248 Results of the mean and standard deviation of the soil loss and sediment concentration in control and conservation
 249 treatments

Component	Treatment	Variable	Study events							
			E1	E2	E3	E4	E5	E6	E7	E8
Soil loss (g)	Control	<i>M</i>	44.97	18.16	28.2	17.61	19.17	16.68	16.81	11.82
		<i>SD</i>	9.31	3.74	1.94	1.69	5.16	2.29	3.38	1.87
	Biochar	<i>M</i>	32.72	13.72	20.22	13.46	12.59	13.63	13.85	9.51
		<i>SD</i>	13.46	1.89	9.46	0.38	1.91	4.31	1.35	1.69
(%) Changes percent			-27.22	-24.44	-28.32	-23.57	-34.33	-18.33	-17.6	-19.55
Sediment concentration (g l ⁻¹)	Control	<i>M</i>	4.54	1.57	0.91	1.61	1.53	1.84	1.4	1.59
		<i>SD</i>	0.53	0.09	0.32	0.09	0.09	0.15	0.18	0.13
	Biochar	<i>M</i>	4.18	1.49	0.85	1.51	1.34	1.66	1.28	1.47
		<i>SD</i>	1.31	0.07	0.21	0.22	0.08	0.51	0.04	0.21
(%) Changes percent			-7.8	-5.06	-6.77	-6.1	-12.32	-9.88	-8.53	-7.56

250 E1 to E8 are the dates of eight rainfall events during the experiment, including 2022.01.06, 2022.01.15, 2022.03.04, 2022.04.30, 2022.11.27,
 251 2023.06.13, 2024.02.06, and 2024.02.20.

252

253 According to Table 4, the biochar conservation treatment led to a moderate reduction in
254 runoff volume, averaging approximately 20% compared to the control. These findings suggest
255 that biochar positively influences soil permeability and hydraulic properties, ultimately
256 reducing runoff volume. This observation aligns with previous studies, such as Gholami et al.
257 (2019), which highlighted the beneficial effects of biochar in mitigating runoff and soil loss, as
258 well as Zhi-guo et al. (2017), who demonstrated biochar's role in runoff reduction. Additionally,
259 Bayabil et al. (2015) reported improvements in soil hydraulic properties with the use of oak and
260 charcoal biochar, while Sadeghi et al. (2016) found reductions in runoff within small erosion
261 plots. Abel et al. (2013) further supported biochar's effectiveness in enhancing soil permeability
262 and hydraulic characteristics. Table 5 reveals that biochar application resulted in an average
263 reduction of 24% in soil loss and 8% in sediment concentration. The percentage of change
264 observed in biochar-treated plots during specific events aligns with findings from Peng et al.
265 (2016), Zhi-guo et al. (2017), and Gholami et al. (2019) who highlighted the significant role of
266 biochar's high carbon content in enhancing soil particle cohesion, thereby aiding in erosion
267 control.

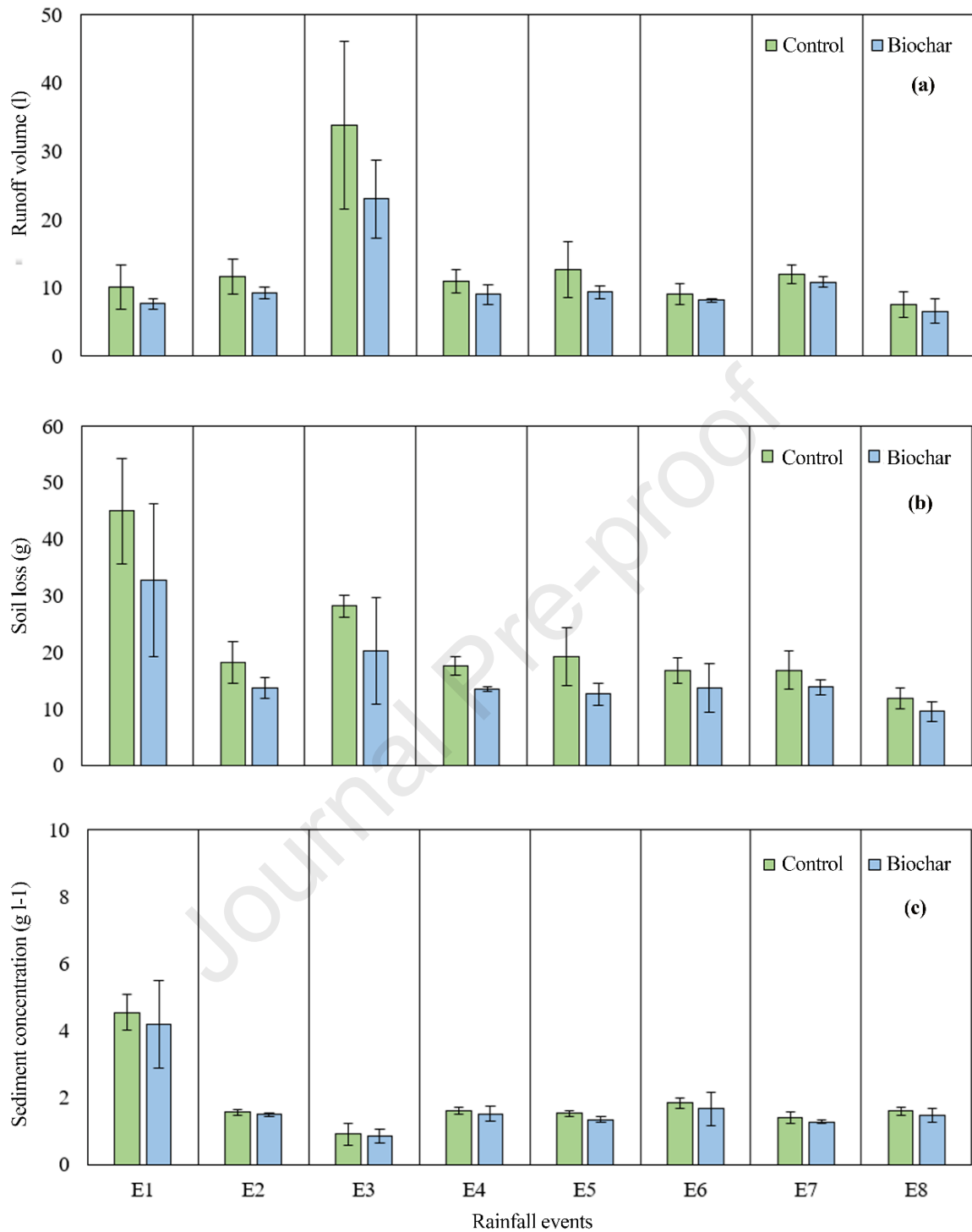
268 Figure 6 shows the average components of runoff volume, soil loss, and sediment
269 concentration in the control and biochar plots under erosive and effective rain events (rainfall
270 that leads to runoff generation). The normality of the dataset was assessed using the Kolmogorov-
271 Smirnov test (Massey, 1951), which confirmed that all measurements of runoff volume, soil loss,
272 and sediment concentration from both control and biochar-treated plots followed a normal
273 distribution. To compare the mean values of the studied components between treatments, a paired
274 t-test was conducted, with results presented in Table 6. The analysis revealed that the application of
275 biochar amendment significantly reduced runoff volume and soil loss, with a significance level of
276 99%. However, the comparison of mean values indicated no statistically significant difference in

277 sediment concentration, suggesting that soil loss plays a direct role in influencing surface runoff

278 volume.

279

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280
 281 **Figure 6.** Means of the runoff volume (l) (a), soil loss (g) (b), sediment concentration (g l⁻¹) (c), in the control
 282 and biochar plots. E1 to E8 are the dates of eight rainfall events during experiment, including 2022.01.06,
 283 2022.01.15, 2022.03.04, 2022.04.30, 2022.11.27, 2023.06.13, 2024.02.06, and 2024.02.20.
 284

285

286 **Table 6**
 287 Results of the Paired samples test for the runoff volume, Soil loss and sediment concentration

Paired Sample T-Test	Runoff Volume	Soil Loss	Sediment Concentration
Sig. (2-tailed)	0.009	0.001	0.174

288

289 The significant reduction in observed runoff volume clearly indicates an increased infiltration
 290 rate treated soils. This finding strongly aligns with the known mechanisms through which biochar
 291 influences soil water dynamics (Acharya et al. 2024). Specifically, the enhanced porosity resulting
 292 from biochar application creates more pathways for water entry and retention, leading to a greater
 293 capacity for infiltration and consequently, a reduction in surface runoff (Park et al., 2023).

294 The findings of this study align with those of Gholami et al. (2019), who reported that the
 295 presence of biochar in small erosion plots contributed to increased soil granulation, enhanced
 296 infiltration, and delayed runoff onset. However, these results contrast with Briggs et al. (2005),
 297 who suggested that soil treated with biochar exhibits greater hydrophobicity due to its higher
 298 hydrocarbon content. Smetanova et al. (2013) examined the effects of biochar derived from wood
 299 chips and tree bark on erosion control in laboratory-scale plots, concluding that biochar application
 300 reduced soil erodibility and runoff volume. Similarly, Fister et al. (2014) investigated biochar's
 301 role in soil loss mitigation using field plots and simulated rainfall, while Jien and Wang (2013)
 302 studied the biochar impacts in laboratory and field conditions and they found that the biochar had
 303 the significantly effects in reducing soil loss. Additionally, Yin et al. (2023) introduced a critical
 304 perspective on biochar's influence on soil erodibility, emphasizing that its impact on surface runoff
 305 varies based on soil conditions and rainfall intensity. Their findings indicate an initial increase in
 306 runoff at the beginning of the experiment, followed by a shift in trend after successive rainfall
 307 events.

308 The properties of the recorded erosive rainfall events in the study area during the experimental
 309 period are presented in Table 2. The rainfall duration (280–1190 min), rainfall height (7.1–25.9
 310 mm), I_{30} (1.8–7.6 mm h⁻¹), KE (0.88-3.87 MJ ha⁻¹ mm⁻¹), and EI₃₀ (1.58-20.89 MJ mm ha⁻¹

311 h^{-1}) were calculated for these events. Rainfall events E1 (2022.01.06) and E2 (2022.01.15)
312 lacked high-resolution (10-minute interval) rainfall records; therefore, event-based rainfall
313 erosivity indices could not be determined. Based on the observed data and meteorological gauge
314 station records, the E3 rainfall occurred on Mar 04, 2022 ($D = 1190 \text{ min}$; $I_{30} = 5.4 \text{ mm h}^{-1}$; EI_{30}
315 $= 20.89 \text{ MJ mm ha}^{-1} \text{ h}^{-1}$). During this event, the measured runoff volumes were 33.77 and 23.0
316 L, and the soil losses were 28.20 and 20.22 g, from the control and biochar plots, respectively
317 (Tables 4 and 5). Among all events, this rainfall (E3) exhibited the greatest rainfall height,
318 duration, and erosivity, along with the highest runoff volume conservation percentage
319 (31.89%). The corresponding soil loss conservation percentage (28.32%) was also substantial.
320 The final recorded erosive rainfall, E8 (Feb 20, 2024), had a duration of 620 min; $I_{30} = 1.8 \text{ mm}$
321 h^{-1} and $EI_{30} = 1.58 \text{ MJ mm ha}^{-1} \text{ h}^{-1}$. This event produced runoff volume of 7.53 L and 6.6 L,
322 and soil losses of 11.82 and 9.51 g, from the control and biochar plots, respectively (Tables 4
323 and 5). Although the E8 event had the lowest erosivity and consequently the smallest runoff
324 volume and soil loss, it did not yield the lowest conservation percentages in runoff volume
325 (12.39%) and soil loss (19.55%).

326 Table 7 summarizes the statistical relationships (R-squared value and Pearson correlation)
327 between runoff volume and soil loss from the control and biochar plots, and the rainfall
328 characteristics (H, D, AI, I_{30} , KE and EI_{30}). The Results indicated strong correlation between
329 runoff volume (for both control and biochar plots) and rainfall characteristics, particularly H,
330 D, and KE. Moreover, Soil loss from both plots showed strong relationships with KE and EI_{30} .

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337 **Table 7**338 The *R*-squared value and Pearson Correlation between runoff volume and soil loss with rainfalls characteristics.

<i>R</i> -squared value		H	D	AI	I30	KE	EI30
Runoff volume	Control	0.9307*	0.7235*	0.0014	0.0490	0.9052*	0.6346
	Biochar	0.9292*	0.7557*	0.0017	0.0450	0.9235*	0.6467
Soil loss	Control	0.1663	0.4483	0.0344	0.1906	0.8931*	0.7428*
	Biochar	0.1536	0.5109	0.0416	0.2239	0.9628*	0.8263*
*. Good <i>R</i> -squared value							
Pearson Correlation		H	D	AI	I30	KE	EI30
Runoff volume	Control	0.965**	0.851*	-0.035	0.202	.951**	0.797
	Biochar	0.964**	0.869*	-0.039	0.212	.961**	0.804
Soil loss	Control	0.408	0.669	0.187	0.437	.945**	.862*
	Biochar	0.392	0.714	0.206	0.474	.981**	.909*

339 *. Correlation is significant at the 0.05 level (2-tailed).

340 **. Correlation is significant at the 0.01 level (2-tailed).

341 H (rainfall height), D (rainfall duration), AI (average rainfall intensity), I30 (rainfall maximum 30-min intensity), KE (rainfall
342 kinetic energy), EI30 (rainfall erosivity index).

343

344 *3.2 Effect of biochar on soil properties*

345 Table 8 presents the measured values of MWD, P, M, pH, EC, SOC, and Ch-a in soil
346 following the application of biochar amendment. The measurements were taken across two
347 treatments (control and biochar) over four six-month intervals (Sample 1 to Sample 4).
348 Additionally, Table 9 summarizes the results of the variance analysis conducted on these
349 components. Figure 7 shows the comparison of average soil properties in control and treated
350 plots at four sampling times.

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359 **Table 8**
 360 Results of aggregate mean weight diameter (MWD), soil porosity (P), soil Moisture (M), pH, electrical
 361 conductivity (EC), soil organic carbon (SOC) and chlorophyll-a (Ch-a) in control and conservation treatments

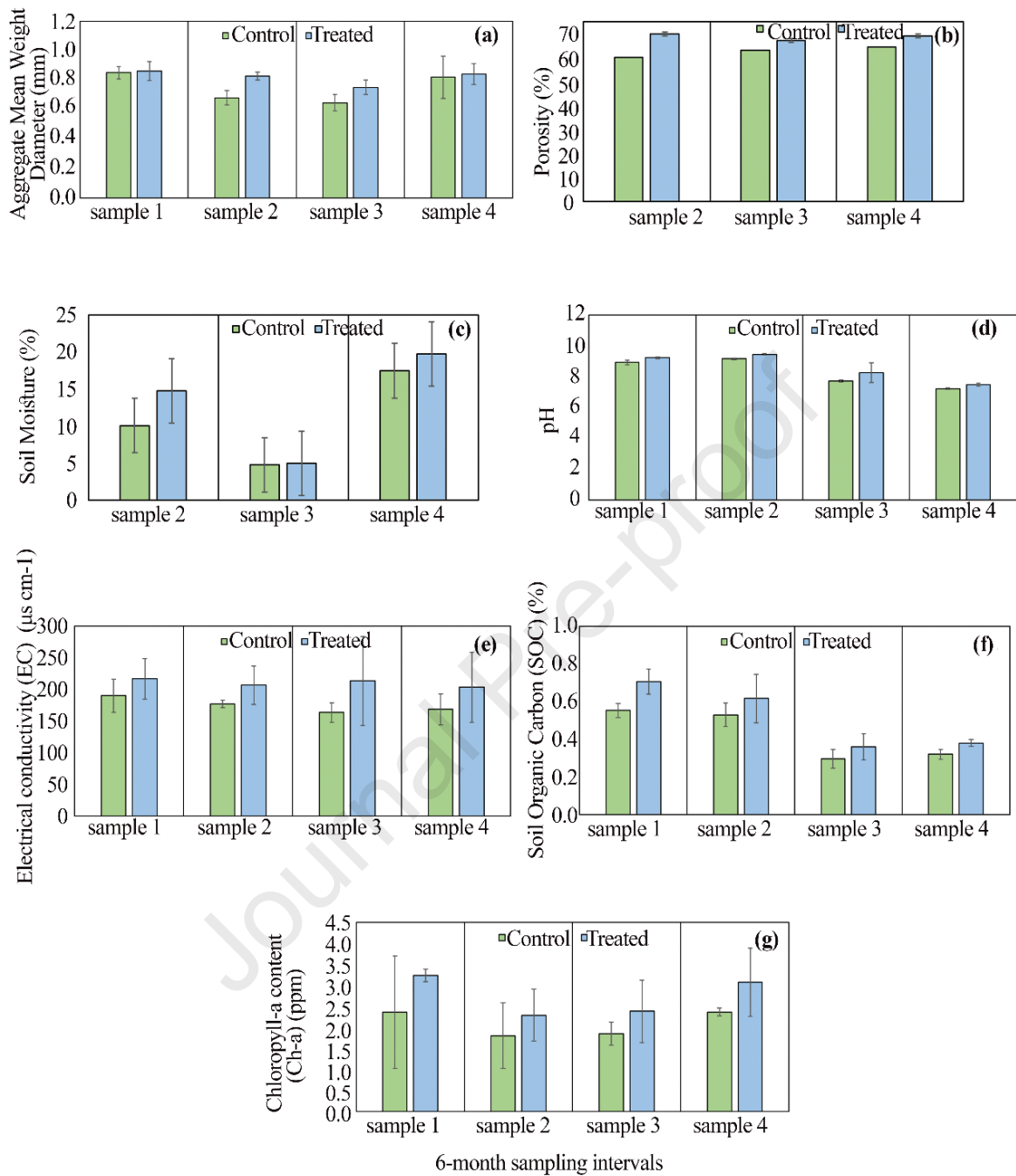
Variable	Treatment	Sample1	Sample2	Sample3	Sample4
MWD (mm)	Control	0.85	0.68	0.65	0.82
	Biochar	0.86	0.83	0.75	0.84
	Changes percent (%)	1.27	21.52	16.09	2.69
P (%)	Control	No Data	60.2	63.17	64.56
	Biochar	No Data	69.9	67.29	69.1
	Changes percent (%)		16.04	6.52	7.03
M (%)	Control	No Data	10.07	4.8	17.49
	Biochar	No Data	14.83	5.01	19.76
	Changes percent (%)		47.34	4.53	13
pH	Control	8.93	9.17	7.73	7.23
	Biochar	9.23	9.47	8.27	7.50
	Changes percent (%)	3.36	3.27	6.90	3.69
EC ($\mu\text{s}/\text{cm}$)	Control	190.0	176.7	163.3	168.3
	Biochar	216.7	206.7	213.3	203.3
	Changes percent (%)	14.04	16.98	30.61	20.79
SOC (%)	Control	0.55	0.53	0.30	0.32
	Biochar	0.71	0.62	0.36	0.38
	Changes percent (%)	27.71	16.35	21.35	18.75
Ch-a ($\mu\text{g}\cdot\text{g}^{-1}$)	Control	2.36	1.80	1.85	2.36
	Biochar	3.23	2.29	2.38	3.07
	Changes percent (%)	37.01	27.22	28.88	30.04

362 Sample 1 to Sample 4 indicate soil sampling times at six-month intervals after biochar application (2022.04.30, 2022.11.29, 2023.05.02, and
 363 2023.12.21). changes percent (%) = (Biochar – Control) / Control *100

364 **Table 9**
 365 The analysis of variance results in different treatments for the studied variables
 366

Dependent	Source	Type III Sum of	df	Mean of Square	F	Sig.	Partial Eta
MWD	Biochar	0.03	1	0.03	6.045	0.026	0.274
	Time	0.09	3	0.03	6.24	0.005	0.539
	Biochar \times Time	0.019	3	0.006	1.287	0.313	0.194
P (%)	Biochar	168.3	1	168.3	5.52	0.037	0.315
	Time	11.35	2	5.67	0.186	0.832	0.030
	Biochar \times Time	28.44	2	14.22	0.467	0.638	0.072
M (%)	Biochar	26.305	1	26.3	8.48	0.013	0.414
	Time	566.45	2	283.22	91.34	0.000	0.938
	Biochar \times Time	15.55	2	7.77	2.50	0.123	0.295
pH	Biochar	0.73	1	0.73	12.69	0.003	0.442
	Time	15.17	3	5.06	87.30	0.000	0.942
	Biochar \times Time	0.07	3	0.02	0.39	0.760	0.069
EC	Biochar	7526.04	1	7526.04	5.23	0.036	0.246
	Time	1078.13	3	359.38	0.25	0.860	0.045
	Biochar \times Time	478.13	3	159.38	0.11	0.953	0.020
SOC	Biochar	0.05	1	0.05	11.40	0.004	0.416
	Time	0.42	3	0.14	32.59	0.000	0.859
	Biochar \times Time	0.01	3	0.00	0.65	0.595	0.108
Ch-a	Biochar	2.55	1	2.55	4.97	0.040	0.237
	Time	2.79	3	0.93	1.82	0.185	0.254
	Biochar \times Time	0.14	3	0.05	0.09	0.964	0.017

367 Mean weight diameter (MWD), soil porosity (P), soil Moisture (M), pH, Electrical conductivity (EC), Soil organic carbon (SOC), and
 368 Chlorophyll-a content (Ch-a) after biochar application (2022.04.30, 2022.11.29, 2023.05.02, and 2023.12.21).
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Figure 7. Comparison of the average on soil properties in control and treated plots, (a): mean weight diameter (MWD) (mm), (b): Soil porosity (P), (c): Soil moisture (M), (d): pH, (e): electrical conductivity (EC), (f): soil organic carbon (SOC), (g): chlorophyll-a content (Ch-a). Sample 1 to Sample 4 indicate the sampling time of soil at six-month intervals after biochar application (2022.04.30, 2022.11.29, 2023.05.02, and 2023.12.21).

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379 3.2.1 Effect of biochar on aggregate stability

380 Aggregate stability was assessed by measuring specific pore diameter and evaluating the
381 MWD index at four six-month intervals following biochar application in both control and
382 treated plots (Table 8). The results indicate that the highest average MWD index (0.86 mm)
383 was observed in the first sample from the biochar treatment, while the lowest (0.65 mm) was
384 recorded in the third sample from the control treatment. The second and third samples exhibited
385 incremental changes of 21.52% and 16.09%, respectively. A comparative analysis of mean
386 MWD values across the four time intervals for both treatments is presented in Figure 7. Table
387 9 summarizes the variance analysis results of the MWD index in biochar and control treatments.
388 The separate impact of biochar was statistically significant at the 95% confidence level, while
389 the effect of time was significant at the 99% level. The effect sizes were large for both factors.
390 Several studies have reported positive effects of biochar on soil stability. For example, Ibrahim
391 et al. (2021) found that different levels of date palm waste biochar improved MWD and
392 enhanced overall aggregate stability. Additionally, Sun et al. (2021) concluded in a six-year
393 field experiment that corn biochar serves as a significant factor in increasing soil aggregate
394 stability due to its role in enhancing MWD.

395 The findings suggest that biochar amendment significantly influenced aggregate stability.
396 Six months after application, the MWD index in both conservation and control plots showed
397 similar values. However, after the second six-month interval, the biochar treatment
398 demonstrated a noticeable improvement, with a percentage increase of approximately 21.5%
399 compared to the control. By the third period-1.5 years after the experiment began-measurements
400 indicated a 16% increase in MWD under biochar treatment relative to the control. Finally, after
401 two years, the values in both treatments returned to levels comparable to those observed in the
402 first period. Changes in soil aggregate stability over time appear to align with seasonal weather
403 patterns, which may be influenced by fluctuations in rainfall and temperature-key factors

404 confirmed by Dimoyiannis (2009). The observed temporal dynamics of MWD likely reflect
405 more complex mechanisms than seasonal climate changes. Based on the present study's
406 findings, biochar exhibited its most pronounced effect on soil aggregate stability and structure
407 approximately one year after application. Following soil incorporation, biochar undergoes
408 surface oxidation and functionalization, increasing its reactivity and potential for organic–
409 mineral interactions (Cheng et al., 2006). These aging processes may enhance associations
410 between biochar, mineral particles, and organic matter, thereby promoting aggregate
411 stabilization. In addition, microbial colonization and the subsequent release of microbially
412 derived binding agents can strengthen aggregate formation through biological binding
413 mechanisms (Liang et al., 2010; Sun et al., 2021). The delayed peak in MWD approximately
414 one year after application may therefore correspond to the time required for biological
415 integration. Furthermore, the initial increase in SOC may have stimulated microbial activity
416 through a priming effect (Kuzyakov et al., 2009), whereas over longer periods, shifts in
417 microbial turnover and carbon redistribution within aggregates may have reduced the relative
418 treatment effect, leading to convergence between biochar and control plots. Overall, these
419 patterns likely reflect a dynamic balance between biological stimulation and carbon
420 stabilization processes.

421

422 *3.2.2 Effect of biochar on P and M*

423 The percentages of P and M components in three successive samplings for both control and
424 biochar-treated plots are presented in Table 8. (Data for these two components were not
425 available at the first sampling time.) Figure 7 illustrates the comparison of mean values of the
426 components affected by the biochar amendment. The highest value of P, amounting to 69.9%,
427 belongs to the first soil sample taken from the surface of the biochar-treated plots, while the
428 lowest value, 60.2%, corresponds to the first soil sampling from the surface of the control plots.

429 According to the results, the mean porosity in the treated plots showed percentage changes of
430 16.04, 6.52, and 7.03, respectively, over time compared with the control plots. The percentage
431 changes in component M across the three sampling times were 47.34, 4.53, and 13%,
432 respectively. Maximum percentage changes for these two parameters were observed in the first
433 year of the study. Based on the analysis of variance in Table 9, the effect of the biochar
434 amendment on total porosity was statistically significant at the 95% confidence level.
435 Moreover, the effect of biochar application was significant at the 95% level, and the effect of
436 time elapsed was significant at the 99% level. However, the interaction effect between biochar
437 and time on these components was not significant.

438 Biochar is a lightweight material with a lower density than soil minerals; its application reduces
439 bulk density due to decreased soil mass per unit volume, thereby lowering soil compaction
440 (Burrell et al., 2016). As reported by researchers (Lehmann and Joseph, 2009; Herath et al.,
441 2013), the addition of biochar improves soil texture, permeability, and overall physical
442 properties of the soil, consequently decreasing bulk density and increasing porosity. Owing to
443 its lower density compared to mineral soil, biochar—depending on soil texture and application
444 rate—can reduce bulk density and enhance soil porosity (Park et al., 2023; Acharya et al., 2024).
445 Incorporation of biochar into soil also modifies pore size distribution and enhances soil water
446 retention capacity. The increased pore volume provides favorable space for water storage within
447 the soil (Yu et al., 2013). Furthermore, the high specific surface area of biochar contributes to
448 improved soil water-holding capacity as a result of its addition. Accordingly, the results of the
449 present study are consistent with the findings of several previous studies (Yu et al., 2017; Zhou
450 et al., 2019; Acharya et al., 2024), which also confirm the significant relationship between
451 biochar application and enhanced soil moisture retention.

452

453 *3.2.3 Effect of biochar on pH and EC*

454 The variations in average pH and EC factors, along with their percentage changes over
455 time in control and treated plots following biochar application, are presented in Table 8. The
456 average pH values ranged from 7.23 to 9.46, with the lowest recorded in the control plot during
457 the final sampling and the highest observed in the treated plot during the second sampling.
458 Similarly, the average EC varied between 163.3 and 216.6, with the lowest value found in the
459 control plot in the third sampling and the highest detected in the treated plot in the first
460 sampling. Notably, both components exhibited their highest percentage changes in the third
461 interval. As indicated in Table 9, biochar application had a statistically significant effect on pH
462 at the 99% confidence level and on EC at the 95% confidence level. Additionally, analysis of
463 variance demonstrated that the effect of time on pH was significant at the 99% confidence level.
464 Moreover, the effect sizes for biochar on pH and EC, as well as for time on pH, were substantial.
465 However, time did not exert a significant effect on EC, nor did the interaction between biochar
466 and time significantly impact pH and EC. Figure 7 illustrate the pH and EC trends across four
467 time intervals for both control and conservation treatments. Based on sequential sampling
468 results, changes in treated plots relative to controls were assessed as both incremental and
469 effective for these two soil chemical parameters. On average, soil pH increased by 4.5%, while
470 EC exhibited a 20.5% rise. The incorporation of biochar, characterized by its alkaline pH,
471 contributed to elevated soil pH (Liang et al., 2006; Sohi et al., 2010; Kameyama et al., 2012;
472 Zhao et al., 2024; Sharma et al., 2025). Biochar acidity is influenced by factors such as soil pH,
473 biomass type, pyrolysis temperature, and surface charge properties (Gul et al., 2015). Liu et al.
474 (2024) found that biochar application increased soil pH by an average of 11%, with the greatest
475 effects occurring in acidic soils. Furthermore, the positive impact of biochar treatment on EC
476 has been reported in this and other studies (Song et al., 2015; Zolfi-Bavariani et al., 2016;
477 Sharma et al., 2025).

478

479 3.2.4 Effect of biochar on SOC

480 The impact of biochar application on the SOC component over time is presented in Table
481 8. Percentage changes in SOC within treated plots compared to control plots were observed as
482 27.71%, 16.35%, 21.35%, and 18.75% across four sampling periods. The lowest recorded
483 average occurred in the third sampling of the control plot, while the highest was found in the
484 first sampling of the treated plots. According to the variance analysis results in Table 8, biochar
485 amendment and time each had a statistically significant effect on SOC at the 99% confidence
486 level, and both factors exhibited large effect sizes. However, the interaction effect between
487 biochar and time on SOC was not significant. A comparative analysis of SOC across four time
488 intervals in control and conservation treatments is illustrated in Figure 7.

489 The findings of this study indicate that the incorporation of biochar as a carbon source had
490 a positive and significant impact on SOC content. Lawrinenko and Laird (2015) attributed the
491 increase in SOC following biochar application to the direct contribution of carbon within
492 biochar. Specifically, a portion of biochar-derived organic carbon integrates into soil carbon
493 reserves, enhancing soil organic matter levels, while another fraction undergoes oxidation,
494 leading to the formation of negatively charged functional groups. Biochar is widely regarded
495 as a stable form of carbon, with its primary role in soil being carbon deposition (Kameyama et
496 al., 2012). Researchers emphasize that one of the most critical applications of biochar is carbon
497 fixation and the subsequent enrichment of SOC (Jindo et al., 2014). Zhao et al. (2024) reported
498 increased SOC levels following biochar application, with findings from Chen et al. (2024a)
499 indicating that the rise ranged from 10.7% to 46.3%, depending on biochar dosage. The
500 utilization of carbon-rich materials such as biochar is also recognized as an effective strategy
501 for soil stabilization, organic matter preservation, and carbon sequestration (Kammann et al.,
502 2011). By storing SOC, biochar facilitates long-term carbon accumulation (Glaser et al., 2002).
503 Research by Wang et al. (2024) further demonstrated that biochar application led to a 33%

504 increase in topsoil organic carbon after a decade. In the present study, following more than two
505 years of biochar application, SOC values in treated plots exhibited an 18.75% increase
506 compared to control plots, reinforcing the long-term effectiveness of biochar in enhancing soil
507 carbon content.

508

509 *3.2.5 Effect of biochar on Ch-a*

510 The variation in average Ch-a content over time in control and biochar-treated plots, along
511 with their percentage changes, is presented in Table 8. Across all four soil sampling stages, Ch-
512 a exhibited a consistently increasing trend, with an average increase of 31%. As shown in Table
513 9, the results of the variance analysis indicate that biochar amendment had a statistically
514 significant effect on Ch-a content at the 95% confidence level, with a substantial effect size.
515 However, the influence of time and the interaction between biochar and time were not
516 statistically significant. A comparative analysis of Ch-a across four time intervals in control and
517 conservation treatments is illustrated in Figure 7.

518 Ch-a in soil is closely linked to organic matter content and microbial activity, making it an
519 important indicator of soil health and quality. The findings of this study suggest that increased
520 Ch-a levels in treated plots compared to control plots reflect enhanced microbial activity in the
521 soil. Specifically, Ch-a content is directly associated with cyanobacterial biomass within soil
522 biocrusts (Keesstra et al., 2019). Castle et al. (2011) demonstrated that factors such as soil type,
523 moisture levels, and extraction methods can influence Ch-a values in biological soil crusts.
524 Additionally, Bolan et al. (2023) reported that biochar enhances the adhesion of colloidal soil
525 particles by promoting microbial development. The study by Moyo et al. (2025) further
526 confirmed that rising Ch-a levels indicate improved photosynthetic activity in cyanobacteria,
527 reinforcing the notion that biochar amendments contribute to biological processes in the soil.

528

529 *3.3 Practical feasibility and application considerations*

530 The use of *Populus nigra* branches for biochar production provides a strategy to valorize
531 abundant, low-value biomass generated by regional wood-processing industries in northwestern
532 Iran. For this study, an application rate of 32.5 t ha⁻¹ was selected to assess the potential for soil
533 improvement and conservation under field conditions, rather than to define an economically
534 optimized rate. Local biomass availability is sufficient to support this rate, as roughly 22% of
535 mature poplar biomass consists of branches and pruning residues (Zhang et al., 2016), which
536 are largely underutilized. Large-scale implementation would require coordinated collection,
537 pyrolysis capacity, transport, and mechanized incorporation. While economic feasibility was
538 beyond the scope of this study, literature shows that optimal application rates can differ from
539 agronomic maxima, and future evaluations should consider indicators relevant to soil
540 conservation, including avoided soil loss, reduced sediment transport, enhanced carbon
541 sequestration, and ecosystem service benefits. Dose–response studies are recommended to
542 determine the minimum effective rate and to evaluate long-term soil carbon stability across
543 different soil types and textures.

544

545 **4 Conclusion**

546 The use of various soil amendments has garnered significant attention in water and soil
547 conservation research. While numerous laboratory studies have validated biochar's
548 effectiveness in improving soil properties, the present study was conducted to examine the
549 impact of biochar derived from Tabrizi poplar trees (*Populus nigra*) on runoff, sediment, and
550 the physical, chemical, and biological characteristics of soil under natural rainfall conditions,
551 utilizing USLE plot-scale analysis. An evaluation of biochar's protective effects on runoff
552 volume, soil loss, and sediment concentration revealed statistically and practically significant
553 reductions of approximately 20%, 24%, and 8%, respectively, compared with the control. These
554 results confirm the strong potential of biochar to mitigate water erosion under natural rainfall

555 condition. While biochar demonstrated robust short-term mitigation of soil and water losses,
556 comprehensive techno-economic assessments are warranted to evaluate the cost effectiveness
557 and feasibility of achieving sustained performance under high application rates for long-term,
558 large-scale field implementation. Comparative analysis indicated a significant difference
559 between biochar-treated soil and control soil regarding runoff volume and soil loss.
560 Consequently, the findings suggest that biochar amendment may serve as a viable strategy for
561 protecting abandoned dryland fields in semi-arid regions.

562 The study further demonstrated that biochar conservation treatment exerted a positive and
563 significant influence on soil physical characteristics, which also varied significantly over time.
564 Regarding chemical properties, the results indicate that biochar notably affected pH, EC, and
565 SOC, with these components exhibiting significant differences compared to control samples.
566 Moreover, pH and SOC underwent considerable changes over time. Ch-a, another critical
567 parameter analyzed, displayed significant variations in response to biochar treatment and
568 temporal progression. Based on the findings, the application of biochar produced from Tabrizi
569 poplar tree branches at 420°C for three hours is deemed beneficial, efficient, and biologically
570 advantageous for soil and water conservation in abandoned rainfed areas of semi-arid regions.
571 Biochar, as a stable organic material with high water and nutrient absorption capacity, enhances
572 soil properties by improving soil structure and aggregate stability, thereby reducing erosion and
573 displacement. These improvements contribute to soil preservation, mitigate erosion's
574 detrimental effects on local ecosystems and water resources, and enhance soil fertility through
575 increased microbial diversity.

576 Overall, the study underscores biochar's potential as an effective strategy for managing
577 water and soil resources in agricultural and natural environments. The findings not only advance
578 knowledge of biochar's effects on soil but also provide valuable insights for policymakers and
579 farmers in optimizing soil and water management practices. Given the complexity of

580 environmental processes under natural climatic conditions, further research employing
581 extended time scales and smaller sampling intervals is necessary to yield more precise results.
582 One of the study's limitations was accessibility to rain gauge stations and the study site.
583 Therefore, future studies should explore soil components in greater detail, assess long-term
584 biochar effects on carbon stability, and investigate its impact across various soil types with
585 differing textures and organic matter content.

586

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590

591 **Declaration of competing interest**

592 The authors declare that they have no known competing financial interests or personal
593 relationships that could have appeared to influence the work reported in this paper.

594

595 **Author contributions**

596 **Author A:** Conceptualization, Data curation, Formal analysis, Methodology, Resources,
597 Software, Visualization, Writing - original draft. **Author B:** Conceptualization, Formal
598 analysis, Investigation, Methodology, Project administration, Supervision, Validation, Writing
599 – review & editing. **Author C:** Conceptualization, Project administration, Supervision, Writing
600 – review & editing. **Author D:** Conceptualization, Investigation, Methodology, Project
601 administration, Supervision, Writing – review & editing.

602

603 **Data availability**

604 The datasets generated during the current study are available in the Mendeley Data
605 repository, <https://data.mendeley.com/datasets/pn4xfy2j8g/1>

606

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Declaration of interests

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