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Assessing the Role of Air Nanobubble-Saturated Water in Enhancing Soil Moisture, Nutrient Retention, and Plant Growth

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Abstract: Nanobubble-saturated water (NBSW) has received significant attention in water management in recent years. Therefore, three parallel experiments (E1, E2, and E3) were conducted on two silty loam soils (one with 12.11% higher clay) and sandy loam soil, with additional biochar amendments in each soil type, to assess air NBSW's impact on soil moisture, nutrient retention, and plant growth. The results revealed increased soil moisture retention in the sandy loam and silty loam soils with a lower clay content. It reduced the K^+ input compared to conventional watering without highly affecting the amount of leached-out substances. Biochar amendment significantly reduced the TDS losses from silty loam with a higher clay content and reduced the leaching of NO_3^-, Ca^{2+}, and K^+ from sandy loam soil. Air NBSW enhanced the stomatal conductance in California pepper plants in silty loam and sandy loam soils but had no effect on silty loam with a higher clay content. A decrease in chlorophyll concentrations and stomatal conductance was observed when air NBSW was combined with biochar in sandy loam soil. The study highlighted that air NBSW alone does not significantly affect water and nutrient retention or key plant parameters. However, its combination with biochar can enhance agricultural water management and sustainability by increasing soil moisture retention and reducing nutrient leaching.

Keywords: air nanobubble-saturated water; soil moisture; nutrient retention; biochar amendment; plant

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1. Introduction

Climate change and poor water resource management are leading to increased water scarcity [1–4]. The use of innovative technologies is essential due to the limitations of traditional irrigation techniques in both saving water and maintaining soil health. Indeed, increasing soil aeration has gained attention for its potential to improve water use efficiency and crop productivity. Micro–nanobubbles (MNBs) are bubbles with diameters typically sized between 200 nm and 50 µm [5]. Their small diameter, as well as their zeta potential, large specific surface area, and high pressure, lead to unique characteristics such as stability, a long storage period, high air solubility, and strong adsorption [6–8]. These characteristics make them ideal for delivering gases in the presence of contaminants [9]. Micro–nanobubble aeration is highly effective in oxygen transfer within liquid phases and is valuable for enhancing enzyme activity, accelerating the rates of chemical oxygen demand, and ammonia removal [10]. MNB-based water treatments are potentially being applied in various sectors, including industry and agriculture [11]. Research has shown various benefits of nanobubbles in agricultural applications. For instance, Park and Kurata [12] found that the application of air microbubbles promoted lettuce growth compared to air macrobubbles. Similarly, Ebina et al. [13] reported that air nanobubble water significantly promoted the height and length of the leaves of and the aerial fresh weight of Brassica campestris compared to conventional water.

In terms of their stability, air nanobubbles were stable for a long period in an ethanol aqueous solution but did not produce significant free radicals compared to CO_2 nanobubbles [14]. Oxygen nanobubble water had a significantly higher dissolved oxygen concentration immediately after generation compared to air nanobubble water, which promoted the growth of Brassica campestris more effectively than air nanobubble water [13]. Meanwhile, air nanobubbles reduce the chemical oxygen demand and significantly improve water quality parameters, which makes them beneficial for environmental applications, while CO_2 nanobubbles can effectively enhance plant growth and productivity by improving the photosynthesis efficiency in crops, which leads to beneficially utilizing CO_2 emissions. Ramiro et al. discovered that using nanobubbles led to a greater presence of microorganisms, resulting in better water quality [15], which aligns with the potential benefits of micro–nanobubble technology in enhancing soil fertility and nutrient absorption [16,17]. According to recent research by Lyu et al. [18] and Wu et al. [19], these implications could have an essential role in helping remediate polluted environments and revive degraded ecosystems.

According to Wang and Wang [20], air nanobubbles are a cost-effective and highly efficient solution that can be produced at a large scale through techniques like hydrodynamic cavitation and hydraulic air compression. Air nanobubbles, alongside other types of nanobubbles, such as N_2, O_2, H_2, Ar, and CO_2, demonstrate the potential for a diverse gas supply and highlight their versatility and broad applicability in different fields [21]. Moreover, Agarwal et al. [5] and Khan et al. [22] reported that air nanobubbles have been documented to increase the efficiency of water purification and chemical water treatment.

In recent years, MNBs' potential as a sustainable solution for water treatment has been recognized [23]. Nanobubble technology (NBT) significantly enhances water quality by increasing the dissolved oxygen levels, minimizing pollutants, and eliminating contaminants like heavy metals, organic pollutants, and bacteria, which can play an important role in sustainable agricultural development. Overall, NBT has been found to have the potential to solve many agricultural and water treatment challenges [24]. Nanobubbles can enhance the surface tension between water molecules, facilitating the penetration of water into the soil and thereby improving water absorption by plant roots [25]. Recent studies have shown that in agriculture, nanobubbles can increase water and nutrient absorption, boost crop yields, and decrease the need for chemical usage [20]. The environmental impact of NBs is significant, and they can be used in many products and processes, including carbon capture and storage, surface coatings, cleaning agents, and enhanced aeration in ponds and reservoirs [26–29]. Hu and Xia [30] examined the efficiency of using ozone micro–nanobubbles (MNBs) to remediate groundwater that was contaminated with organic substances. Recent studies by Kim and Han [31] have shown that hydrogen nanobubbles have high potential in the remediation of soils contaminated with copper, therefore adding to the growing body of research that shows NBs' success in environmental restoration. Considering these advancements, gaps remain in understanding the specific impacts of air nanobubble-saturated water on soil moisture dynamics, water leaching behavior, and plant responses, both independently and in combination with soil additives, in silty loam soils with varying clay contents and sandy loam soils. This offers new insights into how soil texture influences the effectiveness of NBSW. Air NBSW was used in this study because air nanobubbles provide a balanced mixture of gases and have uniform and stable physical and chemical properties. Moreover, using air nanobubbles is easier to implement, requiring no specific equipment to supply the gas, therefore making it a practical choice for numerous applications.

The objectives of this study were to (1) investigate the impact of ambient air NBSW on the soil moisture dynamics in silty loam and sandy loam soils compared to conventional water; (2) evaluate the water losses through leaching and the leached substances using air NBSW compared to conventional water; (3) evaluate the impact of air NBSW on the growth parameters (i.e., physiological indicators like chlorophyll concentration and stomatal conductance) of California pepper plants in silty loam and sandy loam soils at various growth stages.

2. Materials and Methods

2.1. Experimental Design and Treatments

Three parallel experiments (E1, E2, and E3) were performed at Vytautas Magnus University in Kaunas, Lithuania, from 23 January to 30 August 2023. The experiments were divided into two time periods, a pre-planting phase and a post-planting phase (from 11 April onwards), to examine the impact of ambient air NBSW on soil moisture, leached-out water quantity and quality, and the physiological parameters of California pepper plants across silty loam and sandy loam soils commonly found in Lithuania.

Each experiment focused on a distinct soil type and consisted of nine buckets. All the buckets were standardized to the same size, with a 22 cm height and a 0.055 m^2 surface area. Details of these scenarios are presented in Table 1.

Table 1. Selected scenarios demonstrating soil types, watering treatment, and biochar amendments.

Group	Scenario No.	Soil Type	Watering Type	Soil Composition	Biochar Composition	Biochar Mass Fraction	Total Nitrogen (N) (%)	Total Phosphorus (P) (mg/kg)	Total Potassium (K) (mg/kg)
E1-A	1	Silty loam with higher clay content	Conventional water	clay: 13.95% silt: 64.25% sand: 21.8%	No		0.202	464	2893
E1-B	2	Silty loam with higher clay content	Air nanobubble water		No				
E1-C	3	Silty loam with higher clay content (amended with biochar)	Air nanobubble water		Made by FLUID S.A., Poland (5% of dry soil weight) 80.6% C, 0.96% H, 0.33% N, 0.03% S, 0.10% P, 664.8 mg/kg P_2O_5, 957.6 mg/kg Fe, 0.27% K, 0.52% Ca, 0.13% Mg	>2 µm (0.301%) 2–63 µm (47.11%) 63–2000 µm (52.58%)			
E2-A	4	Silty loam	Conventional water	clay: 1.84% silt: 68.44% sand: 29.71%	No		0.306	499	3101
E2-B	5	Silty loam	Air nanobubble water		No				
E2-C	6	Silty loam (amended with biochar)	Air nanobubble water		Made by FLUID S.A. *	Refer to **			
E3-A	7	Sandy loam	Conventional water	clay: 0.60% silt: 27.96% sand: 71.45%	No		0.350	580	2955
E3-B	8	Sandy loam	Air nanobubble water		No				
E3-C	9	Sandy loam (amended with biochar)	Air nanobubble water		Made by FLUID S.A. *	Refer to **			

* The biochar composition is consistent with the values outlined in Scenario 3. ** The biochar mass fraction is consistent with the values outlined in Scenario 3.

Watering was implemented according to the experimental design, with a focus on comparing the effects of air NBSW and conventional water addition across different soil types and biochar amendment soil buckets. Watering was carried out when the soil moisture dropped to 65–70% of the field capacity. The same water used for conventional watering was saturated with nanobubbles to produce the air NBSW. Nanobubbles were produced through pressurized gas–liquid mixing using the HLYZ-002 model of nanobubble generator manufactured by HOLLY (Holly Technology, PRC), sourced from atmospheric air. According to the information provided by the manufacturer, the bubble diameter ranges from 80 nm to 20 µm with a predominant average diameter of 200 nm, facilitating a gas–liquid dissolving rate exceeding 95%. The watering events for each experiment lasted from 5 to 10 min. Before planting, uniform watering was applied to ensure consistent moisture levels across all the buckets. Distinct watering patterns emerged post-planting.

After each watering event, the water that leached out from the soil buckets was collected in bottles attached to the bottom of the buckets for further analysis. The experimental setup, which included soil buckets with connected bottles, is shown in Figure 1.

(a) (b) (c)

Figure 1. (**a**) Test samples arranged for experimentation. (**b**) Plant development stage. (**c**) The experimental setup for leached-out water collection.

2.2. Soil Moisture

To assess the water balance within the experimental setup, the soil moisture content, the water input, the leached-out water, air temperature, and relative humidity were measured. The soil moisture content was calculated using the following equation:

$$\Delta W_n = R_n - AE_n - D_n \quad (1)$$

where n represents a time step of every three hours; ΔW_n represents the change in the soil moisture content (mm); R_n stands for the water input into the soil (mm); AE_n represents the amount of water lost due to evapotranspiration (mm); D_n represents the water leached out (mm).

Air temperature and relative humidity were monitored at three-hour intervals (equating to eight observations per day) from 23 January 2023 to 30 August 2023. The average air temperature during the experiment was 21.3 °C (ranging from 13.8 °C to 29.8 °C), and the average air humidity was 56.4% (ranging from 36.9% to 71.1%). Moreover, planting occurred when the air temperature was approximately 19.4 °C, with an air humidity of 56.7%.

The total water input during the post-planting phase for each scenario was as follows: Scenario 1: 15.46 L; Scenario 2: 15 L; Scenario 3: 10.89 L; Scenario 4: 15.99 L; Scenario 5: 12.73 L; Scenario 6: 11.34 L; Scenario 7: 14.07 L; Scenario 8: 12.34 L; and Scenario 9: 16.37 L. All the buckets within the same group in each experiment received identical watering. Afterwards, the leached-out water from each bucket was collected and quantified to ensure precise volume measurements. During the experiment, a data logger (GP2 Data Logger, Delta-T devices, Cambridge, UK) connected to soil moisture probes (ML3 ThetaProbe, Delta-T devices, Cambridge, UK) was implemented to quantify and monitor the soil moisture content. Therefore, each of the nine scenarios featured a soil moisture data logger integrated with soil moisture probes, with the rod ends vertically positioned at a depth of 15 cm. This setup allowed us to determine the average moisture content in both the upper and lower layers of the root zone, at between 1/3 and 3/4 of the bucket's depth.

2.3. Nutrient and Other Substances Losses

Watering was periodically performed to artificially create water leachate. At each watering event, both the applied water and the leached-out water were subjected to chemical analysis. The water collected in each scenario was gathered by collecting and mixing the leached-out water from three buckets of the same group. The following substances were monitored: nitrate (NO_3^-), sulphate (SO_4^{2-}), nitrite (NO_2^-) and ammonia (NH_4^+). These were determined using a MaxiDirect Photometer MD600 (Lovibond®, Amesbury, UK) with powder reagents. When the NO_3^- levels exceeded 177 mg/L (40 mg/L N), a Horiba LAQUAtwin NO_3^- meter (Horiba Ltd., Kyoto, Japan) was used. Total Dissolved Solids (TDS) and pH levels were determined using a portable HI9813-51 multimeter (Hanna® Instruments Ltd., Leighton Buzzard, UK), with a range of measured TDS values from 0 to 2000 mg/L. If the concentration of TDS in the samples exceeded the maximum measurable value, these values were recorded as overrange. Phosphates (PO_4^{3-}) were determined using an HI-713 colorimeter. The chemical oxygen demand (COD) was determined using an HI-83099-02 COD multimeter photometer. The amounts of calcium (Ca^{2+}), potassium (K^+), total iron (Fe^{3+}), and magnesium (Mg^{2+}) were determined using an HI 83099 COD multi-parameter photometer (Hanna® Instruments Ltd., Leighton Buzzard, UK).

2.4. Plant Chlorophyll and Stomatal Conductance

California pepper (*bot. Capsicum annuum*) growth parameters were monitored across different stages of plant development to assess the impact of ambient air NBSW. The California pepper plant was chosen for its adaptability and ability to grow in nutrient-poor environments. Its well-defined stem structure, preference for well-drained soil, sensitivity to waterlogging, and nutrient deficiencies allowed for measurements of the plant at different stages of growth. Moreover, the California pepper plant has gained significant attention in greenhouse cultivation in Lithuania. Its irrigation demands are a topic of ongoing discussion due to their implications from both economical and practical perspectives, emphasizing the plant's importance in this region. Full-spectrum LED grow lights with an intensity of 4000–12,000 lux at 25–40 cm above the top of the plants were used. Illumination took place for 14 to 16 h per day, from growth to flowering. The light intensity was measured with an LX-8809A light meter (ATP Instrumentation®, Ashby De La Zouch, UK).

On April 24, inorganic fertilizers with NPK contents of 46%, 19%, and 52% (25 g/m^2 of carbamide, 50 g/m^2 of superphosphate, and 10 g/m^2 of potassium chloride), respectively, were applied to the soil surface in each bucket. On 29 June, the same fertilization was repeated.

The plant height and the number of leaves were quantified through direct observation. The chlorophyll concentration was determined using an atLEAF CHL chlorophyll meter (FT Green LLC® Wilmington, DE, USA) by measuring the light transmission through the plant leaves at a wavelength of 660 nm (referring to Zhu et al. [32] and Basyouni and Dunn [33]). The atLEAF units were then converted into the total chlorophyll content (mg/cm^2) using the calibration and conversion guidelines provided by atLEAF. Stomatal conductance was determined using the DECAGON® SC-1 (Pullman, WA, USA) leaf porometer. Measurements were conducted every 10 days at three points on each plant: the uppermost leaf, the middle leaf, and the lowermost leaf. The ambient CO_2 concentration during plant growth ranged from 440 to 640 ppm and was determined using an AZ-7752 Carbon Dioxide (AZ® instrument, Taichung, Taiwan) Detector, respectively.

Seedlings were transplanted (at the 6-leaf stage) into the buckets (one in each), and monitoring of their growth started on 11 April 2023. However, the plants did not reach the maturity stage nor produce fruits, and hence yield evaluation was not achieved. After flowering, the plants showed rapid upward growth but failed to develop fruits, which indicates that the environment was not ideal for specific pepper growing conditions. Further investigations confirmed that the reasons for this were not diseases such as root rot, bacterial wilt, or fungal infections. The lack of pollination and potentially inadequate light conditions were considered the primary factors that contributed to the plants' failure to thrive and reach maturity. However, despite adjusting the lighting setup, no improvement was observed. The actual causes remain unclear; nevertheless, the experiment was terminated on 30 August 2023, and the data presented here reflect the period before and shortly after plant flowering.

2.5. Statistical Analysis

To assess the reliability of the differences between the data sets within each experimental group throughout the study duration, the non-parametric Kruskal–Wallis test was used. This test aimed to determine whether the scenarios with air NBSW in each experiment were significantly different from the conventional watering scenarios. The differences were estimated for the data sets measured during the entire study period and its parts, including the pre-planting and post-planting phases. All the statistical analyses were performed using the PAST (version 4.0) software package.

3. Results

3.1. Soil Moisture

During the entire study period, the soil moisture in experiment E1 ranged from 29.2 to 114 mm. Under existing conditions, scenario 1 had 13% soil moisture retention of the water input with a 6% leaching ratio. Scenario 2 showed a slight increase and retained 14% of the soil moisture with 5% leaching. Scenario 3 achieved the highest efficiency, retaining a remarkable 27% of the water with a near-negligible leaching ratio. The absence of statistically significant differences between scenarios 1 and 2 based on the Kruskal–Wallis test revealed that air NBSW had no effect on the soil moisture retention in the silty loam E1 trials, while significant differences were revealed in scenario 3 compared to scenarios 1 and 2 ($p < 0.010$). The changes in soil moisture across the three scenarios in experiment E1 are shown in Figure 2.

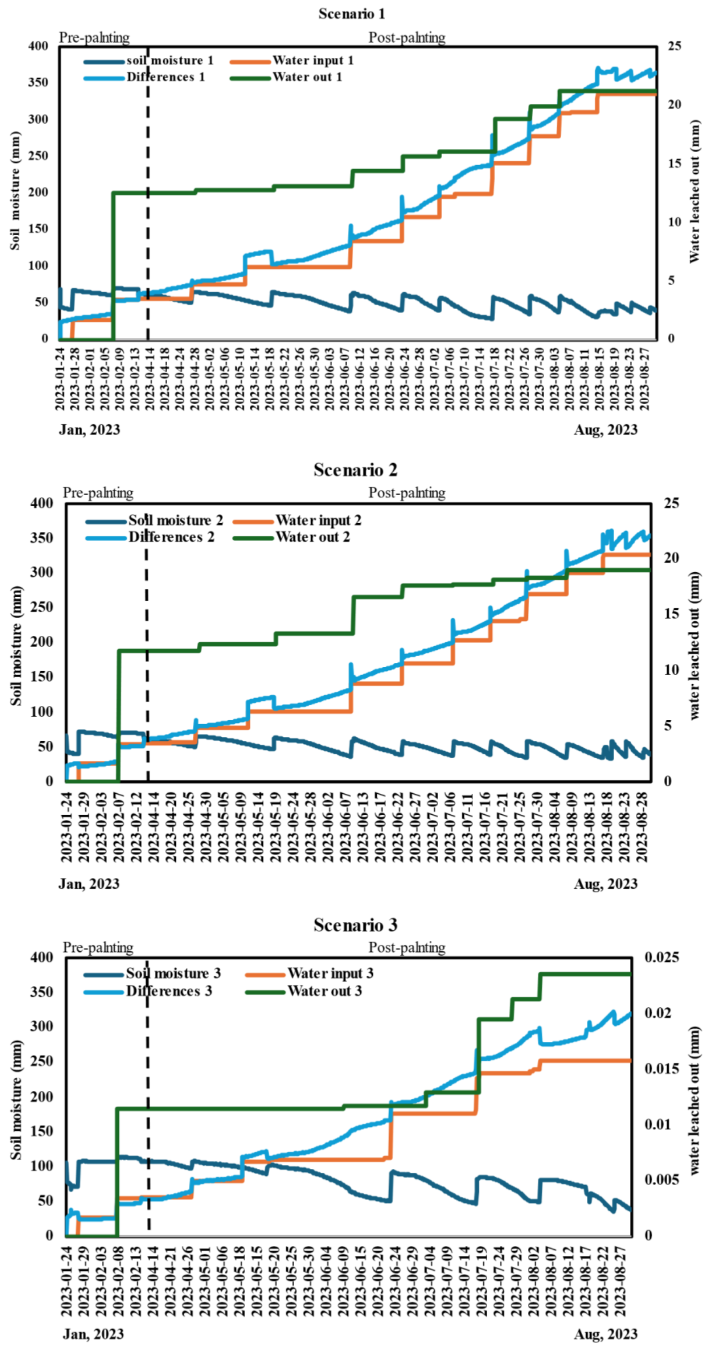

Figure 2. Soil moisture dynamics, water input, and leaching-out in E1 scenarios.

The soil moisture measured in experiment E2 ranged from 28.8 to 128.1 mm. Scenarios 4, 5, and 6 exhibited water retention percentages of 13.56%, 13.67%, and 25.27%, respectively, while the corresponding leaching rates were 6.91%, 6.73%, and 5.58%. The results revealed a statistically significant difference in the soil moisture dynamics between scenarios 4 and 5 ($p < 0.050$). This presumes that NBSW had a higher effect on soil moisture retention. Moreover, a much higher retention was revealed in scenario 6 compared to scenarios 4 and 5 ($p < 0.050$). This confirms that the observed higher soil moisture in scenario 6 compared to scenarios 4 and 5 was achieved due to the effect of the biochar amendment. The dynamics of soil moisture across the three scenarios in experiment E2 are shown in Figure 3.

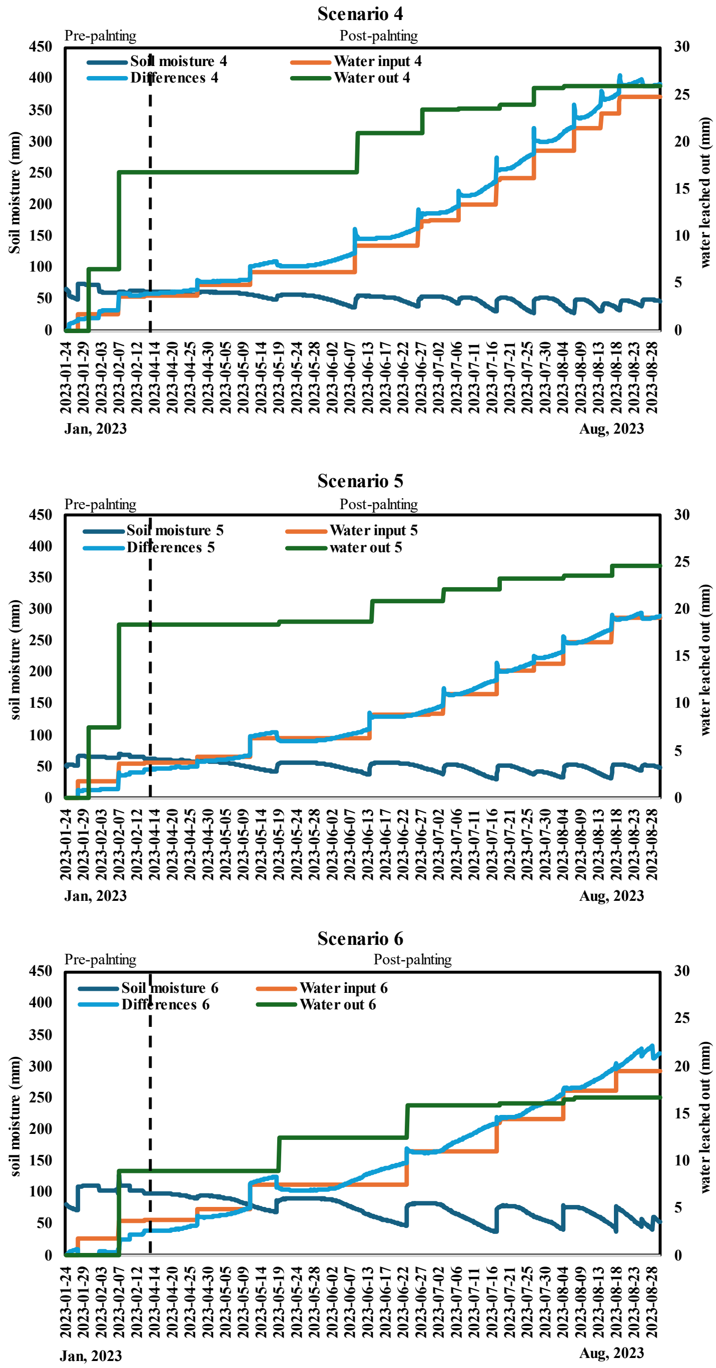

Figure 3. Soil moisture dynamics, water input, and leaching-out in E2 scenarios.

In experiment E3, the differences in soil moisture were statistically significant ($p < 0.050$) among all the scenarios. Moreover, introducing biochar amendments alongside air NBSW in scenario 9 substantially increased the soil moisture content. Scenario 7 exhibited the lowest moisture range (21.2–85.8 mm) and retention (13.54%), with a high leaching ratio (2.4%). Scenario 8 showed a slightly higher moisture range (23.4–88.8 mm) and retention (15.61%) and a lower leaching ratio (2.0%). Scenario 9 demonstrated the most significant effect, with the highest moisture range (40.1–128.1 mm) and retention (19.37%), while achieving a high leaching ratio (3.9%). The changes in soil moisture across the three scenarios in experiment E3 are shown in Figure 4.

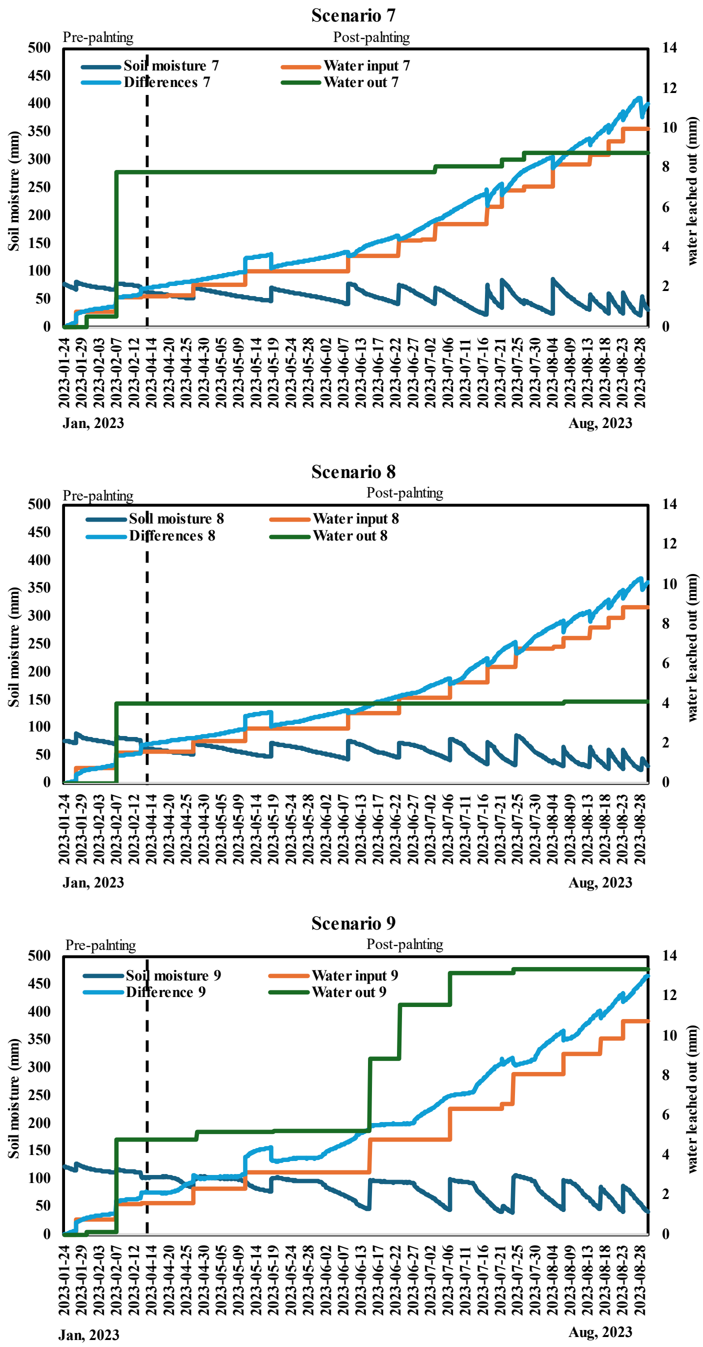

Figure 4. Soil moisture dynamics, water input, and leaching-out in E3 scenarios.

3.2. Nutrients and Other Substances

Investigation of the input water quality revealed no significant differences in pH or TDS nor the amounts of NO_3^-, NO_2^-, PO_4^{3-}, SO_4^{2-}, Ca^{2+}, total Fe^{3+}, or Mg^{2+} between the conventional and air NBSW treatments. However, the amount of K^+ showed a statistically significant difference ($p < 0.050$), with conventional water, displaying 25% higher amounts compared to NBSW. The absence of differences in these parameters allowed us to assume that the inflow water conditions were mostly alike. During the entire study period, the pH values ranged from 6.8 to 7.4 in both conventional water and NBSW. Meanwhile, the amount of NO_3^- displayed some variation in both conventional water and NBSW, ranging from 18 to 57 mg (12–38 mg/L) and 18 to 53 mg (12–35 mg/L), respectively. Similarly, the amount of PO_4^{3-} ranged between 0.8 and 2.8 mg (0.5–1.8 mg/L) in conventional water and 0 and 1.8 mg (0–1.2 mg/L) in NBSW. Conventional water showed a broader range for Ca^{2+}, with values between 18 and 290 mg (12–193 mg/L), while NBSW demonstrated variation within a range of 24 to 255 mg (16–170 mg/L). Likewise, Mg^{2+} varied between 16.5 and 30 mg (11–20 mg/L) and between 22.5 and 34.5 mg (15–23 mg/L). Figure 5 illustrates the range of each substance's amount in both the conventional water and NBSW.

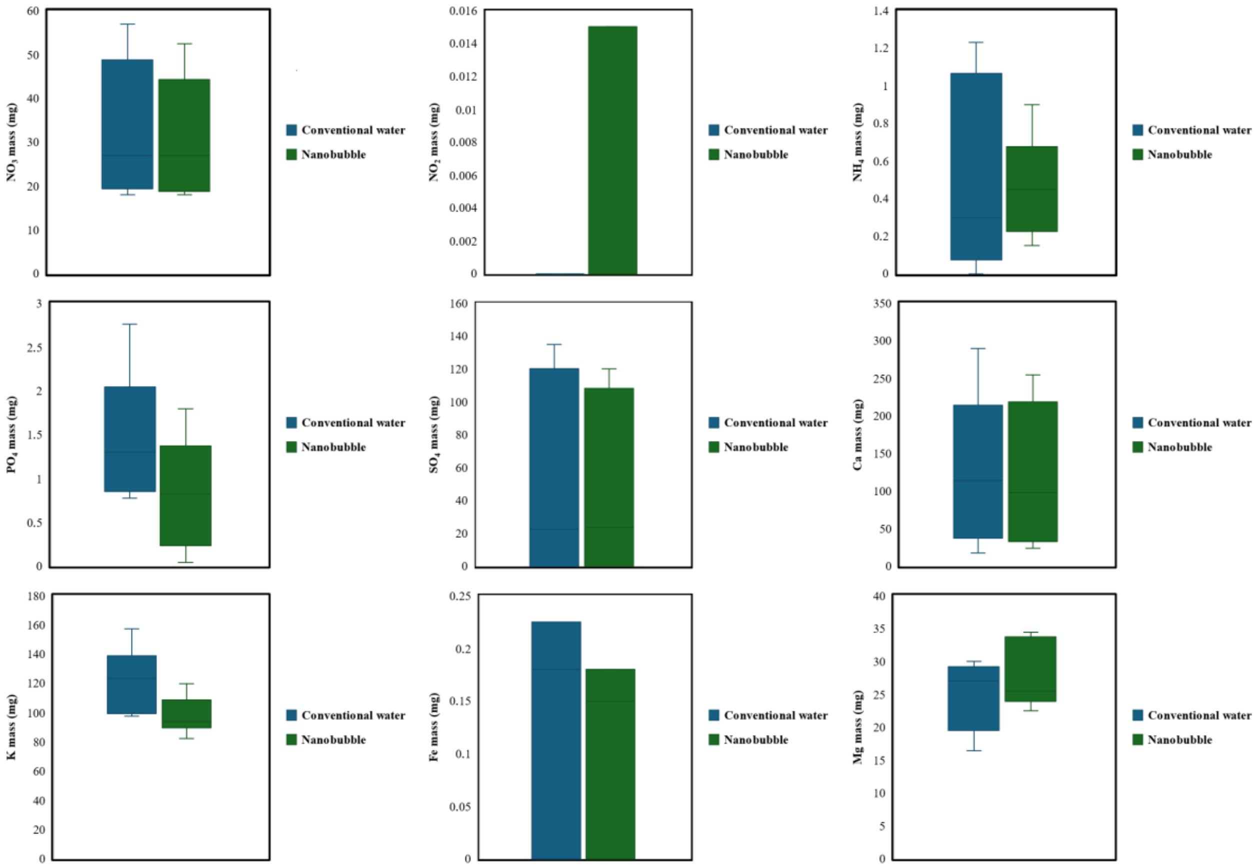

Figure 5. Comparison of various substances in conventional water and NBSW used for watering (Boxplots show the interquartile range from Q1 to Q3 quartiles, with whiskers extending to the smallest and largest values. The means are represented by horizontal lines within the boxes.).

The pH values in the leached-out water ranged from 6.7 to 7.6, from 6.9 to 7.4, and from 6.4 to 7.5 in experiments E1, E2, and E3, respectively, and showed no significant difference between the scenarios in each experiment. In experiment E1, the TDS ranged from 11.7 to 1062 mg (749 to 1750 mg/L), from 24.6 to 988 mg (705 to 1520 mg/L), and from 0.02 to 0.6 mg (642 to 1279 mg/L) in scenarios 1, 2, and 3, respectively. In experiment E2, they varied from 46.6 to 512 mg (875 to 1242 mg/L), from 21.7 to 512 mg (852 to 1740 mg/L), and from 16.6 to 368 mg (754 to 1247 mg/L) in scenarios 4, 5, and 6, respectively. In experiment E3, scenario 7 represented over 2000 mg/L and scenarios 8 and 9 344 to 439 mg (1800 to over 2000 mg/L) and 26 to 486 mg (1138 to 1902 mg/L), respectively.

In experiment E1, scenario 2 showed no significant difference in the TDS present in the leached-out water compared to scenario 1. This indicated that NBSW had an insignificant impact on the TDS compared to those in conventional water. However, scenario 3 showed a significant reduction in TDS losses compared to scenarios 1 and 2, which indicates that biochar effectively reduces the TDS losses in silty loam with a higher clay content.

In experiment E2, the TDS amounts in scenarios 4, 5, and 6 did not show significant differences, indicating that neither NBSW nor biochar amendment significantly impacted the TDS amounts leached out of silty loam soil. Similarly, no significant differences were observed in scenarios 7, 8, or 9 in experiment E3. However, scenario 7 had notably higher TDS losses. While scenarios 8 and 9 appeared to have reduced TDS losses in the leached-out water compared to conventional water, scenario 9 had the lowest losses, which indicates the potential benefit of biochar in reducing the TDS losses leached out of sandy loam soil.

The amount of NO_3^- in experiment E1 ranged from 2 to 420 mg (140 to 610 mg/L) and from 7 to 351 mg (120 to 540 mg/L) and was around zero in scenarios 1, 2, and 3, respectively. In experiment E2, it ranged from 8.5 to 198 mg (160 to 620 mg/L), from 5.6 to 180 mg (170 to 680 mg/L), and from 0 to 41 mg (0 to 220 mg/L) in scenarios 4, 5, and 6, respectively, and in experiment E3, it ranged from 27 to 556 mg (430 to 3100 mg/L), from 57 to 395 mg (330 to 1800 mg/L), and from 1.2 to 255 mg (240 to 1000 mg/L) in scenarios 7, 8, and 9, respectively.

In experiment E1, although the variations in the amount of NO_3^- between scenarios 1 and 2 did not show any significant differences based on the Kruskal–Wallis test, a significant difference was revealed between scenario 3 compared to scenarios 1 and 2 ($p < 0.050$). This implies that biochar contributes to reducing the amount of NO_3^- in leached-out water from silty loam with a higher clay content. Moreover, in experiments E2 and E3, no significant difference was found among all the scenarios.

The amounts of NO_2^- consistently remained at zero or were negligible across all the experiments. There were no significant differences observed between scenarios using NBSW, conventional water, or biochar. Similarly, the results revealed that the amount of NH_4^+ in all the experiments was mostly zero, indicating insignificant variance and no statistically significant difference.

The amount of PO_4^{3-} in experiment E1 ranged from 0 to 1.7 mg (0 to 2.7 mg/L) and from 0 to 1.9 mg (0 to 2.8 mg/L) and was around zero in scenarios 1, 2, and 3. In experiment E2, it ranged from 0 to 0.85 mg (0 to 1.5 mg/L), from 0 to 0.2 mg (0 to 2.5 mg/L), and from 0.5 to 0.8 mg (0.3 to 2.9 mg/L) in scenarios 4, 5, and 6, respectively, and in experiment E3, it ranged from 0 to 0.84 mg (0 to 2.1 mg/L), from 0 to 0.2 mg (0 to 1 mg/L), and from 0 to 0.4 mg (0 to 1.7 mg/L) in scenarios 7, 8, and 9, respectively. The differences in PO_4^{3-} among the scenarios in all three experiments were also statistically insignificant.

The study was expanded to include the additional substances SO_4^{2-}, K^+, COD, total Fe^{3+}, Ca^{2+}, and Mg^{2+}.

In experiment E1, a significant decrease was observed in the amount of K^+ in scenario 3 compared to scenarios 1 and 2. Moreover, a significant decrease was observed in the amount of Ca^{2+} in scenario 3 compared to the NBSW scenario. The range of substances across all the scenarios is presented in Table 2. Additionally, The comparative substance losses from the soil are detailed in Figure 6.

Table 2. Concentration of nutrients and other substances (mg/L) in leached-out water in experiments E1, E2, and E3.

Experiment	Scenario	SO_4^{2-}	COD	Fe^{3+}	Mg^{2+}	Ca^{2+}	K^+
E1	1	77 to 100	0	0	26 to 61	158 to 334	70 to 200
E1	2	80 to 100	0	0	18 to 71	134 to 353	80 to 95
E1	3	close to zero	0	0	close to zero	around zero	around zero
E2	4	5 to 100	0 to 95	0	19 to 25	215	95 to 200
E2	5	5 to 100	0 to 121	0	20 to 46	168 to 261	105 to 195
E2	6	38 to 100	0 to 527	0	16 to 28	132 to 225	150 to 200
E3	7	100	70 to 496	0	0 to 47	400	100 to 125
E3	8	100	382 to 688	0	0 to 64	400	100 to 165
E3	9	100	283 to 405	0	28 to 43	227 to 400	200

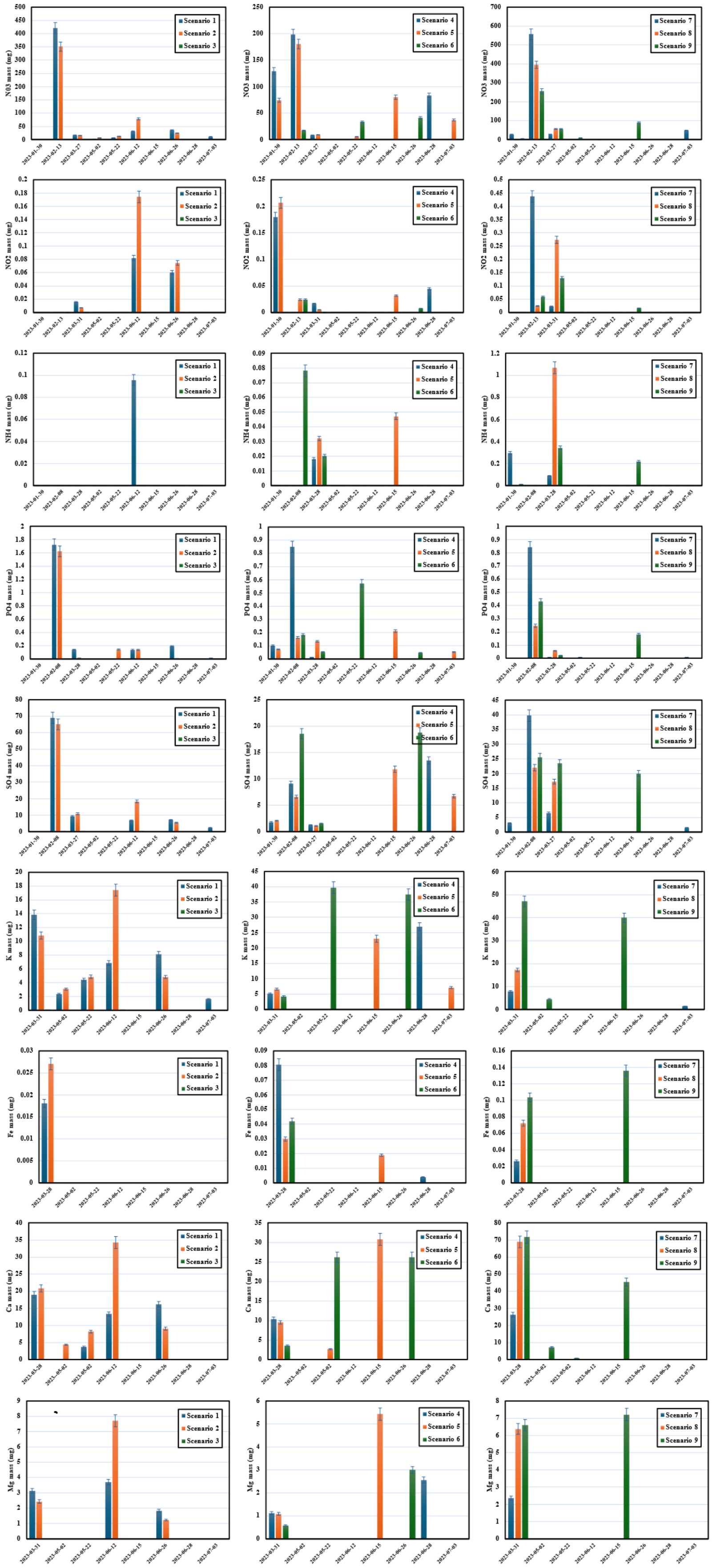

Figure 6. Comparative substance losses from the soil in experiments E1, E2, and E3.

3.3. Plant Growth

3.3.1. Chlorophyll Concentration

The foliar chlorophyll content measured in all the experiments ranged from 10 to 62.3 atLEAF units, corresponding to a total chlorophyll concentration of 0.01 to 0.05 mg/cm^2.

Experiment E1 showed total chlorophyll concentrations of 0.02 to 0.05 mg/cm^2 (Figure 7a). In experiment E2, it ranged from 0.02 to 0.05 mg/cm^2, respectively. In experiments E1 and E2, no significant differences were observed among the scenarios. In experiment E3, the chlorophyll concentration varied from 0.02 to 0.05 mg/cm^2. According to the Kruskal–Wallis test, the results imply a significant reduction ($p < 0.050$) in scenario 9 compared to scenarios 7 and 8. Scenarios 7 and 8 showed 17% and 21.18% higher values than scenario 9, respectively. Further analysis of the relationship between the chlorophyll concentration measurements and the soil moisture content revealed that in silty loam soil, the chlorophyll content (Figure 7) was higher in the biochar-amended scenarios, while in sandy loam soil, scenario 9, despite having the highest soil moisture range, showed the lowest chlorophyll concentration in experiment E3. These observations revealed that a higher soil moisture content may create an array of adverse conditions that affect overall plant physiology, all of which can contribute to lower chlorophyll concentrations. The relationship between soil moisture and total chlorophyll concentration is illustrated in Figure 8.

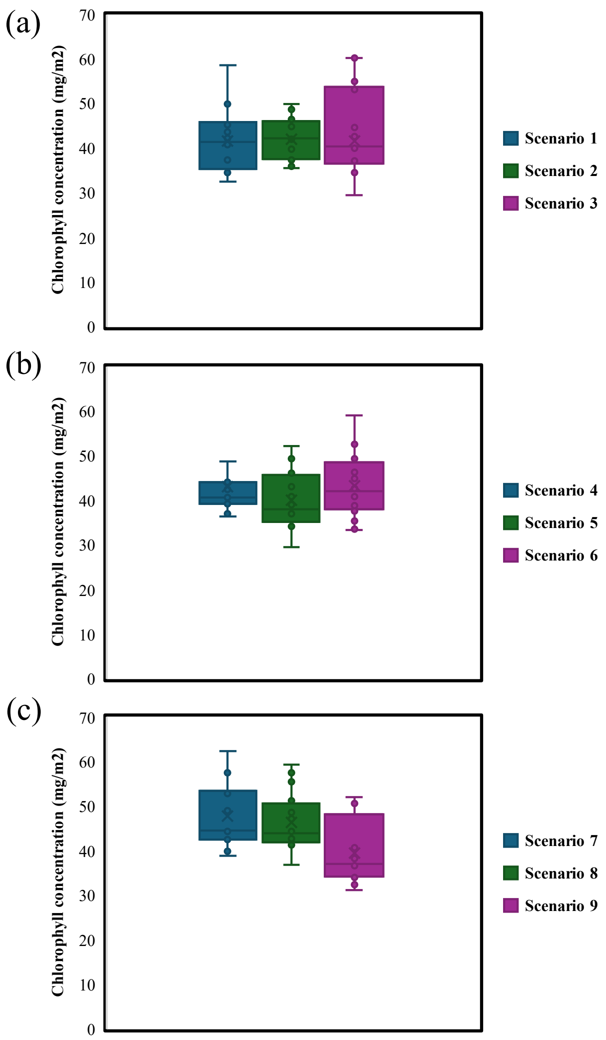

Figure 7. Comparison of chlorophyll concentration in California pepper plants in scenarios E1 (**a**), E2 (**b**), and E3 (**c**) (Each boxplot displays the interquartile range from the first quartile (Q1) to the third quartile (Q3), with whiskers extending to the smallest and largest values. The means are indicated by crosses and medians by horizontal lines within the boxes.).

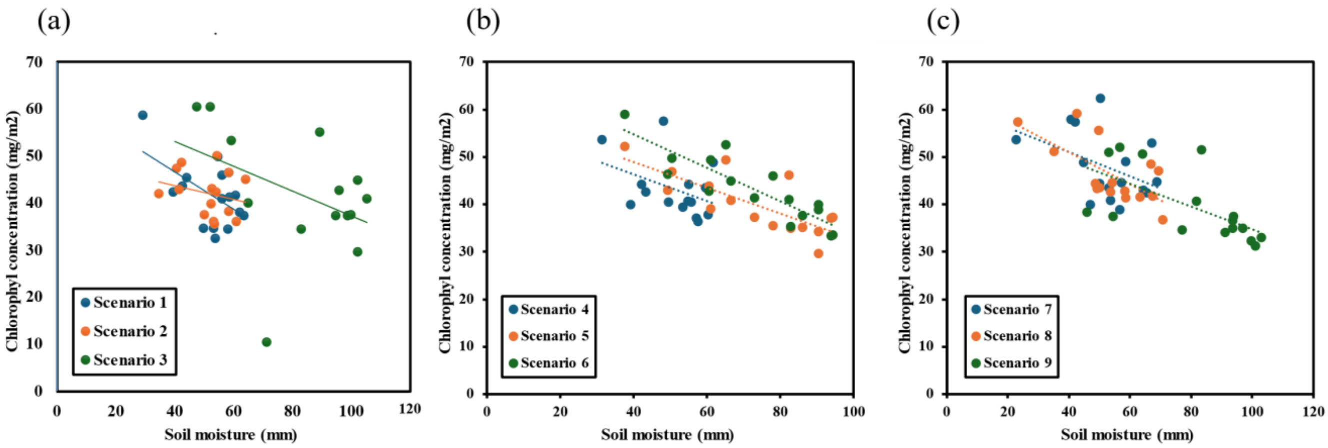

Figure 8. Soil moisture–total chl. relationship in experiments E1 (**a**), E2 (**b**), and E3 (**c**).

3.3.2. Stomatal Conductance

The stomatal conductance in experiment E1 ranged from 34 to 408 mol/m^2/s; in experiment E2, it changed from 23.5 to 355 mol/m^2/s; and in experiment E3, it varied from 42 to 359 mol/m^2/s (Figure 9a–c). No significant differences among different scenarios in each of the experiments were determined. In experiment E1, air NBSW alone had an insignificant effect on stomatal conductance, but scenario 3 showed a significant increase compared to scenarios 1 and 2. In experiment E2, NBSW enhanced stomatal conductance, while scenario 6 showed further enhancement compared to scenarios 4 and 5. In experiment E3, NBSW alone resulted in the highest increase in stomatal conductance, and scenario 9 had the lowest stomatal conductance compared to scenarios 7 and 8. Further analysis revealed that in experiment E1, scenario 3 demonstrated the highest stomatal conductance. This indicates that the plant responds more effectively to a higher soil moisture content (Figure 10a). Similarly, in experiment E2, NBSW enhanced the stomatal conductance, and in scenario 6, which had a higher soil moisture content, there was a further increase in stomatal conductance compared to scenarios 4 and 5. In experiment E3, while NBSW increased stomatal conductance, scenario 9 had the lowest conductance. This finding indicates that the stomatal conductance in plants growing in consistently highly moisture-retentive soil might be lower due to potentially reduced water uptake and transpiration. The response could be caused by a temporary oxygen deficiency in the roots or a reduction in photosynthesis, protecting the plant from excess water accumulation in the tissues. The relationship between soil moisture and stomatal conductance across the scenarios are shown in Figure 10.

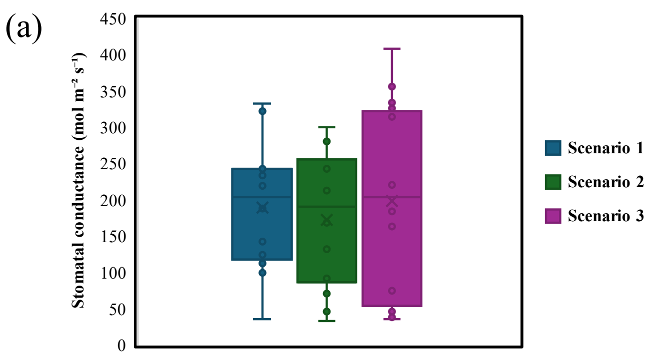

Figure 9. *Cont.*

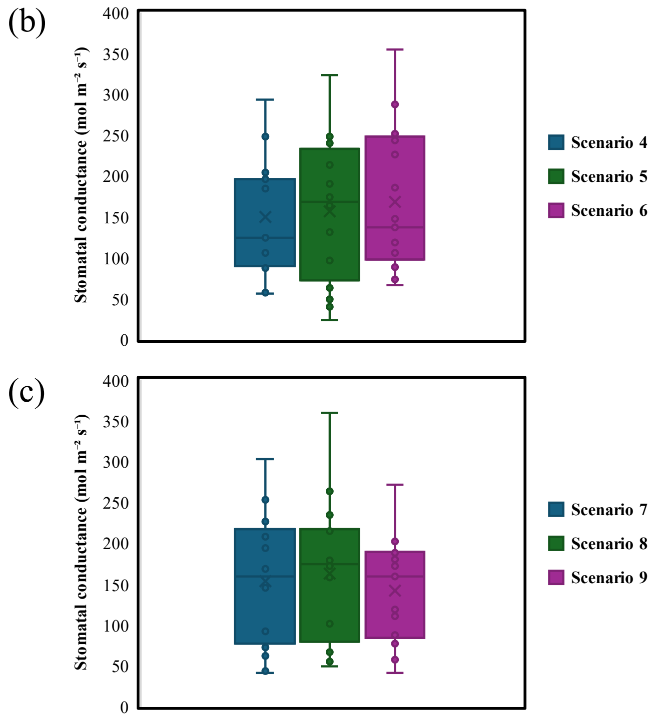

Figure 9. Comparison of stomatal conductance in California pepper plants across various scenarios, E1 (**a**), E2 (**b**), and E3 (**c**). (Each boxplot displays the interquartile range from the first quartile (Q1) to the third quartile (Q3), with whiskers extending to the smallest and largest values. The means are indicated by crosses and medians by horizontal lines within the boxes.)

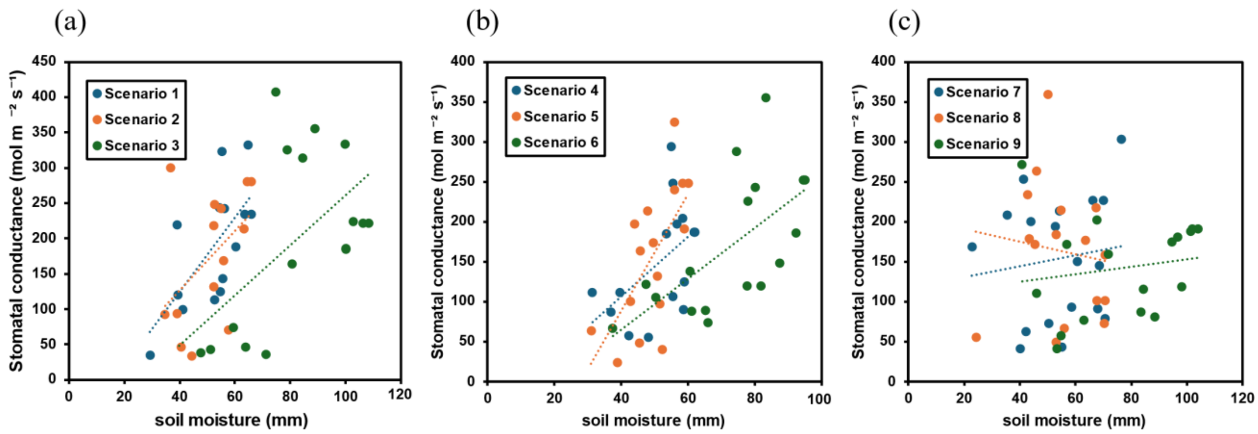

Figure 10. Soil moisture–stomatal conductance relationship in experiments E1 (**a**), E2 (**b**), and E3 (**c**).

4. Discussion

4.1. Soil Moisture

In the experiment in silty loam soil with a 12.11% higher (compared to E2) clay content, air NBSW watering and conventional watering showed no significant differences, retaining 14% and 13% of the water with 5% and 6% leaching, respectively. The presence of micropores in clay soil causes water to have slower movement, which leads to higher water retention. This means that in soil with a higher clay content, the structure itself may create conditions in which water is held more effectively within the soil. Gomboš [34] and Wei et al. [35] reported that the surface of clay particles is negatively charged, which allows them to attract and bond with water molecules. This process naturally increases the water-holding capacity of the soil, making it more effective in soil moisture retention, even without the presence of air nanobubbles. Thereby, in soil with a higher clay content, a relative increase in water retention is harder to achieve.

Moreover, the introduction of biochar combined with NBSW watering showed a significant enhancement in water retention compared to conventional watering and NBSW watering, achieving a retention ratio of 27%, with negligible amounts of leaching. There is no doubt that this is more the effect of the biochar than the nanobubbles. Biochar is known for its porous structure, which can enhance the soil's physical properties, including its water-holding capacity. The enhancement can be attributed to the high surface area and porosity of biochar [36–38], with its potential to influence the soil structure by changing the bulk surface area, pore size distribution, and soil bulk density.

The silty loam soil with a lower clay content (1.84%) in experiment E2 had a looser structure compared to that in experiment E1. This allowed for better movement of water and air through the soil. Air NBSW contributed to an increase in the soil moisture content compared to conventional watering. It is known that nanobubbles can reduce surface tension, remain suspended in water for longer periods, and penetrate deeper into the matrix when water enters the soil, occupying pore spaces and increasing the water retention capacity [22]. The results suggest that this effect is stronger in silty loam soil with a lower clay content. Soils with a lower clay content have larger pores [39]; therefore, it is likely that NBs allow for higher adherence of water to larger soil particles, leading to increased wettability and retention. The observed decrease in leaching (6.7%) showed that nanobubbles may reduce the loss of water and nutrients due to their better interaction with the soil. This aligns with previous research indicating that air nanobubbles can enhance the water retention in soil and improve plant water uptake [12,40,41]. Moreover, biochar combined with NBSW retained an 86.34% higher soil moisture level compared to conventional water and an 84.86% higher level than NBSW. The leaching rates were approximately 19.24% and 17.09% lower, respectively, which showed the clear advantage of biochar addition. According to Downie et al. [42], biochar can absorb and hold water within its porous structure and effectively increase the soil's water-holding capacity. When combined with NBSW, the biochar's pores can be filled with nanobubbles, further increasing the water retention properties. Nanobubbles can occupy the micropores in the biochar, preventing water from draining and reducing leaching. Similar findings were found by Glaser et al. [43], indicating that biochar amendments improve the soil structure by increasing its porosity and aggregate stability, which are important for enhancing water retention and reducing surface runoff.

In the sandy loam soil (experiment E3), air NBSW introduction demonstrated a significant increase in the soil moisture content (higher by 15.28%) compared to conventional watering. According to Carvalho et al. [44], sandy loam soils are characterized by their quick drainage and low water retention capacity due to their coarse texture. However, considering the likely reasons mentioned above, the results of the current study indicate that NBSW has the potential to the increase water retention capacity in sandy loam soil.

While air nanobubbles showed a significant benefit for water retention in sandy loam soil, biochar amendment had a substantially higher impact. Supporting the potential benefits of biochar, Ouyang et al. [45] reported that biochar amendment enhances the formation and stabilization of soil macroaggregates in sandy loam soil. Similar findings by Obia et al. [46] and Verheijen et al. [47] showed that biochar addition to sandy soil leads to a reduction in bulk density and enhances the soil's aggregate stability, porosity, and water-holding capacity.

4.2. Nutrient and Other Substance Losses

The water quality measurements were performed on various substances in both conventional water and air NBSW, as well as in the leached-out water. The findings on the water input demonstrated a significant reduction in the amount of K+, while the variation in the pH and TDS, as well as NO_3^-, NO_2^-, NH_4^+, PO_4^{3-}, SO_4^{2-}, Ca^{2+}, total Fe^{3+}, and Mg^{2+}, between conventional water and NBSW was largely similar. These findings suggest that water saturation with air NBs does not significantly change its chemical composition compared to conventional water. However, Wang and Wang [20] have reported that NBs, due to their small size and high surface area, may facilitate the removal of dissolved gases and other substances from water. The current study supports this finding that K^+ may be one of the constituents that is effectively degassed or removed through the nanobubble saturation process.

Ahmed et al. [48], Shi et al. [49], and Khaled Abdella Ahmed et al. [48] reported that the long-term stability of nanobubbles, caused by a buildup of negative charges at their interface, might explain the observed consistency in the nutrient levels. This creates a repulsive force, thus slowing bubble dissipation. The current study supports these findings, indicating consistency in the nutrient levels for positively charged ions like Ca^{2+}, Mg^{2+}, and NH_4^+. However, for negatively charged ions such as NO_3^- and PO_4^{3-}, the negative NB interface repels these ions. The significant difference in the amount of K^+ can be attributed to the interaction between potassium ions and the charged interface of the NBs. Yasui et al. [50] highlighted that the liquid water surface has a strong affinity to electrons, which leads to a negative charge at the nanobubble interface. This charge can influence the behavior of K^+ ions through electrostatic interactions or changes in local osmotic pressure. Similar findings were observed by Wang, Liu, and Dong [51], indicating that potassium ion retention differs from that of other nutrients.

The measurements on the leached-out water indicated no significant differences in the amounts of NO_2^-, PO_4^{3-}, SO_4^{2-}, COD, Mg^{2+}, or total Fe^{3+} across all three types of soils subjected to conventional watering, air NBSW watering, and the combined treatment of NBSW watering and biochar amendment.

In sandy loam soil, the amended biochar contributed to a slightly higher TDS retention compared to the use of NBSW or conventional watering alone. Ahmed et al. [52] discussed that biochar, due to the properties mentioned above, has a high ability to adsorb and retain various dissolved solids, including nutrients and minerals. When combined with NBSW, biochar's effectiveness in TDS retention was further enhanced due to the improved water retention and soil structure provided by the nanobubbles. Furthermore, in silty loam soil with a higher clay content, the introduction of air NBSW exhibited no significant difference in NO_3^- losses compared to conventional watering, while the incorporation of biochar amendments led to a reduction compared to the scenarios that received air NBSW alone and conventional water. Further studies by Peake et al. [53], Hossain et al. [54], Hagemann et al. [55], Nepal et al. [56], and Yang et al. [57] align with this study, showing that biochar improves nutrient retention and reduces nutrient leaching by improving the soil properties and adsorption capacity. Moreover, biochar amendment significantly reduced the amounts of K^+ and Ca^{2+} leached from the soil when combined with air NBSW. This suggests that biochar is primarily responsible for this decrease compared to conventional watering and NBSW treatment. The results in silty loam and sandy loam soils revealed that NBSW has an insignificant impact on nutrients leaching out compared to conventional watering.

4.3. Plant Growth

In the silty loam soil experiments, air NBSW had an insignificant impact on the chlorophyll concentration. Similarly, biochar also did not show any significant difference in the chlorophyll concentration compared to using NBs and conventional watering. The inherent properties of clay in silty loam soil provide sufficient micropores and lead to soil water retention and nutrient availability. This could reduce the relative impact of NBSW on the chlorophyll content. Moreover, according to Figure 7, amendment with biochar exhibited a marginal increase in the chlorophyll content compared to air NBSW and conventional watering. Kabir et al. [58] reported that biochar enhances the nutrient availability by improving the cation exchange capacity. Furthermore, Bhat et al. [59] showed that the porous structure of biochar provides a favorable habitat for beneficial soil microorganisms, which can enhance nutrient availability and uptake by plants. Kabir et al. [58] reported that microbial enhancement is a key factor in the observed increase in chlorophyll content in biochar-amended soils. Moreover, Feng et al. [60] demonstrated that the addition of biochar reduced soil evaporation and delayed water loss. This characteristic of biochar enhancing the soil moisture retention and delaying evaporation was also noted by Akhtar et al. [61], who reported that biochar under reduced irrigation conditions increased the yield and quality of tomatoes and grapes, indicating a higher plant-available water content. Similarly, studies by Ding et al. [62], Liu et al. [63], and Yang et al. [57] support that biochar helps to regulate the water distribution in the soil.

In the sandy loam soil experiment, no significant difference in the chlorophyll concentration was seen between air NBSW and conventional watering. Moreover, the soil amended with biochar exhibited an excessively high moisture content, which proved unfavorable and impeded plant nutrient uptake. Based on the results observed, it is likely that the roots are deprived of sufficient oxygen, which most probably impedes nutrient uptake. The incorporation of biochar particles differently changes the hydrological conditions in loamy and sandy soils. Libutti et al. [64] reported that silty loam soils are characterized by fine particles, and the addition of biochar likely increases the inter-pores in them. Additionally, Li et al. [65] demonstrated that sandy soil is characterized by more coarse particles, and biochar decreases the inter-pores, which leads to high moisture retention and can lead to overly moist conditions. This outcome implies that most probably, the addition of biochar to sandy loam soil temporary led to excessive moisture retention, potentially leading to waterlogging. Waterlogging can inhibit root respiration and nutrient uptake, thereby reducing chlorophyll synthesis. Ouyang et al. [45] reported sandy soil is more sensitive to the moisture retention effect of biochar compared to silty soil.

In silty loam soil with a higher clay content, air NBSW watering showed no significant difference in stomatal conductance compared to conventional watering, while biochar amendment revealed a higher level. As was mentioned earlier, Downie et al. [42] reported that the porous structure of biochar can enhance the soil's physical properties, including its water-holding capacity. This indicates that under conditions of the optimal soil moisture, plants can maintain open stomata to facilitate gas exchange. Similarly, in silty loam soil, NBSW positively influenced stomatal conductance, exhibiting an increased gas exchange capacity. This shows that an enhanced soil moisture content, due to the stability and penetration of NBSW into the silty soil, can promote better stomatal function. In sandy loam soil, the relationship between soil moisture and stomatal conductance was inefficient, likely due to the highly moisture-retentive soil's reduction in water uptake and transpiration. Although NBSW initially increased the stomatal conductance, biochar amendment resulted in the lowest stomatal conductance. This can be attributed to the fact that excessive soil moisture in sandy loam may lead to adverse effects on stomatal behavior, where oxygen deficiency in the roots triggers stomatal closure to minimize water uptake and transpiration. Vennam et al. [66] highlighted that a high soil moisture content limits plant growth and development by reducing physiological and phenotypic expression. Similar findings were observed by Yan, Zhong, and Shangguan [67], demonstrating that plant water relations are significantly influenced by the available soil moisture, which, in turn, affects stomatal conductance. This can be attributed to biochar's dual effect, indicating that while it improves soil moisture retention, it can also create overly moist conditions that reduce root oxygenation.

Biochar's potential for soil moisture retention and nutrient availability is likely to reduce the need for frequent irrigation and chemical fertilizers, resulting in reduced runoff and utility for more sustainable agricultural practices. Moreover, Alkharabsheh et al. [68] reported that biochar has gained significant attention as an environmental management tool in agriculture. However, the ambiguous impact of biochar highlights the need for specific management practices in sustainable agriculture for specific soil types. Studies by Borchard et al. [69] and Nelissen et al. [70] revealed that the addition of biochar could have negative or no effects on the productivity of crops in sandy loam soil.

5. Conclusions

The results demonstrated the potential of air NBSW to increase soil moisture retention, particularly in sandy loam soil. Silty loam soil with a 12.11% higher (compared to E2) clay content exhibited insignificant differences in moisture retention between watering with conventional water and NBSW. This presumes that the water content of soils with a higher clay content may be less affected by the application of air NBSW than soils with a lower clay content. However, the biochar amendment (5% of dry soil weight) significantly enhanced the soil moisture retention in both the silty loam and sandy loam soils.

The results revealed no significant differences in the amount of most substances (NO_3^-, NO_2^-, PO_4^{3-}, SO_4^{2-}, Fe^{3+}, and Mg^{2+}) between conventional water and NBSW treatments. However, biochar amendments consistently reduced the leaching of certain elements, particularly NO_3^-, K^+, and Ca^{2+}, in both the silty loam and sandy loam soils.

The application of NBSW increased the stomatal conductance in the sandy loam soil, indicating better water use efficiency and gas exchange. However, higher moisture retention due to biochar in the sandy loam soil led to adverse conditions for plant growth, including reduced chlorophyll concentrations. In the silty loam soils, NBSW had no significant impact on stomatal conductance. Conversely, biochar amendments in the silty loam soils consistently increased the chlorophyll content, likely due to enhanced nutrient availability and improved soil structure.

Overall, this study demonstrated that despite its lower cost, ease of implementation, and other benefits, water saturated with air nanobubbles did not significantly affect the water or nutrient retention in the soil or key plant parameters, indicating its limited effectiveness in practical agricultural applications. Therefore, further research should focus on deepening the exploration of the use of nanobubbles generated from gases like O_2, H_2, O_3, N_2, or CO_2, which may offer better results. These findings are relevant to achieving sustainability because optimizing soil moisture and nutrient management through innovative technologies can enhance water use efficiency, reduce environmental impact, and promote resilient agricultural practices, contributing to sustainable food production systems.

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