horticulturae

MDPI

Article

Magnetized Saline Water Modulates Soil Salinization and Enhances Forage Productivity: Genotype-Specific Responses of *Lotus corniculatus* L.

Aurelio Pedroza-Sandoval [1,*], Luis Ángel González-Espíndola [1], María del Rosario Jacobo-Salcedo [2], Isaac Gramillo-Ávila [1] and José Antonio Miranda-Rojas [1]

[1] Unidad Regional Universitaria de Zonas Áridas, Universidad Autónoma Chapingo, Bermejillo 35230, Durango, Mexico
[2] Centro Nacional de Investigación Disciplinaria en Relaciones Agua, Suelo, Planta, Atmósfera (CENID RASPA), del Instituto Nacional de Investigaciones Forestales, Agrícolas y Pecuarias, Km. 6.5 Margen Derecha, Canal de Sacramento, Gómez Palacio 35079, Durango, Mexico
* Correspondence: apedroza@chapingo.uruza.edu.mx

Abstract: Irrigation water salinity poses escalating threats to agricultural sustainability in degraded agroecosystems. This study has investigated the effects of magnetized versus non-magnetized saline water on the soil physicochemical properties and forage productivity of three *Lotus corniculatus* L. genotypes (salt-sensitive ecotype 232098, moderately salt-tolerant San Gabriel, and salt-tolerant Estanzuela Ganador) in arid northern Mexico. A split-plot randomized block design with three replicates assigned saline water treatments (magnetized [MWT] vs. non-magnetized [NMWT]) to main plots and genotypes to subplots. After one year of irrigation, MWT significantly attenuated soil salinization, evidenced by 23% lower electrical conductivity (5.8 vs. 7.2 dS·m^{-1}), a 26% reduced sodium adsorption ratio (6.2 vs. 8.4), and a 41% decreased sodium concentration (20.7 vs. 35.4 meq·L^{-1}) compared to NMWT ($p < 0.05$). Although agronomic traits (stem dimensions, leaf area index, and rhizome proliferation) exhibited salt sensitivity from the third season onward, fresh biomass yield remained unaffected by water treatment. Genotypic differences dominated productivity. Estanzuela Ganador achieved superior biomass in both seasons (288.9 g/rhizome in fall; 184.2 g in winter), outperforming San Gabriel by 15.8% and ecotype 232098 by 56.8% ($p < 0.05$). These findings demonstrate that magnetized saline water irrigation effectively mitigates soil salinity progression, while genotype selection critically determines forage productivity under arid conditions. Estanzuela Ganador emerges as the optimal cultivar for saline irrigation systems in water-scarce regions.

Keywords: magnetized water irrigation; forage production; salt-tolerant genotypes; soil physicochemical properties; saline water; deep-well overexploitation

check for updates

Academic Editors: Lijian Zheng and Juanjuan Ma

Received: 15 March 2025
Revised: 11 April 2025
Accepted: 14 April 2025
Published: 17 April 2025

Citation: Pedroza-Sandoval, A.; González-Espíndola, L.Á.; Jacobo-Salcedo, M.d.R.; Gramillo-Ávila, I.; Miranda-Rojas, J.A. Magnetized Saline Water Modulates Soil Salinization and Enhances Forage Productivity: Genotype-Specific Responses of *Lotus corniculatus* L. *Horticulturae* **2025**, *11*, 428. https://doi.org/10.3390/horticulturae11040428

1. Introduction

Climate change is accelerating, increasing extreme weather events with a high environmental impact on natural resources [1]. The effect of climate change is turning arid zones into marginal areas due to the greater frequency of droughts induced by the hydrological cycle [2]. Agroecosystem degradation is caused by water scarcity and salinity, which deteriorates the soil–plant system in areas irrigated with deep-well water [3].

The intensive use of natural resources in dryland areas causes the overexploitation of aquifer, resulting in a shortage of water with a high salt content [4,5]. In agricultural areas irrigated with saline water, there is a gradual accumulation of salt in the soil, with a negative impact on the chemical soil characteristics and crop growth and yields. According to EOS DATA ANALYTICS [6], more than 5000 acres are being degraded daily by the salinization of irrigation water. Managing soil salinity in its early stages makes it possible to reverse this degradation process.

Innovative strategies are necessary to mitigate the adverse effects of irrigation water salinity in crops to improve the agricultural system in degraded agroecosystems. One such technology is the use of magnetized saline water, which has shown promise in alleviating salinity stress in irrigated agricultural areas depressed by salinity in deep-well irrigation water [7–9]. Magnetic water treatment is based on the principle of Faraday induction, changing the water's physicochemical properties and enhancing the biological and chemical properties of the soil. This magnetizing process reduces the surface tension of water, improves its activity as a solvent, increases the exchange of the liquid in the soil and plants and, therefore, makes electrolytic exchange more efficient [10].

Magnetic water treatment involves passing water through a tubular magnetic field based on magnets with magnetic fluxes of 3000 to 10,000 gauss. This exposure disrupts water molecules, which makes a molecular alignment and an organized movement of the electrons more stable, since the water molecules are dipole [11]. The magnetic treatment through a magnetic field changes the polarity characteristics and hydrogen-bond structure of water; therefore, magnetizing water helps plants to uptake the water as a result of the reorganization of the water molecules. Magnetized water is hexagonal water created by passing water through a specific magnet that activates and ionizes water molecules to change their structure [12].

According to Mamani [13], magnetized irrigation water reduces the effect of salt accumulation in the soil and promotes better osmosis in the plant. This is related to improving the cell penetration process for water transport, nutrient diffusion, and root growth, thereby enabling greater biological production. Yi et al. [14] reported that magnetized saline water improves the water content available to cotton plants, increasing the emergence rate, vigor, height, stem diameter, and leaf area index, as well as improving their chlorophyll content and photosynthesis rate.

Agriculture in northern Mexico relies on irrigation water from deep wells, where aquifers are overexploited, reducing the amount of water extracted, which also has a high salt content [4,15,16]. Soil salinization resulting from using saline water is a serious problem that requires strategies to mitigate the accumulation of salt in the soil [17]. Magnetic water technology in agriculture is a viable alternative for areas depressed by soil salinity, lowering the rate of soil salt accumulation, improving soil permeability, increasing the solubility of minerals, and enhancing plants' water absorption efficiency.

The clover *Lotus corniculatus* L. is proving to be an alternative crop with high potential in different livestock areas due to its adaptational flexibility to water and salinity stress conditions [18,19]. This forage species adapts well to sandy, poorly drained soil and extreme temperatures. The plant can produce high-quality biomass for direct consumption in pastures or for cutting and silage [20,21].

Given the problems resulting from the environmental impacts of intensive water use and the production of fodder for dairy farming in northern Mexico using alfalfa, the diversification of low-water-intensive forage crops is an alternative for agricultural areas with water scarcity and salinity. Additionally, the use of forage species tolerant to soil salinity represents increased potential for marginal agriculture depressed by water scarcity and soil salinity [22,23]. This study aimed to evaluate the use of magnetized and non-magnetized saline water on the growth, development and yield of fresh biomass of different *Lotus corniculatus* L. genotypes in northern Mexico.

2. Materials and Methods

2.1. Geographic Location of the Study Area

The study was carried out in the experimental field of the Unidad Regional Universitaria de Zonas Áridas of the Universidad Autónoma Chapingo in Bermejillo, Mapimí, Durango, Mexico. The region is located between 101°41′ and 104°61′ WL and 24°22′ and 26°23′ NL, at an average elevation of 1100 m. This area has a dry climate, with rain in summer and cool winters, average annual rainfall of 258 mm, and an average annual potential evaporation of 2000 mm. The average annual temperature is 21 °C with a maximum of 33.7 °C and a minimum of 7.5 °C [24]. The texture of the experimental soil was determined by the Bouyoucos method [25] and corresponded to sandy loam with 54%, 32%, and 14% sand, silt, and clay, respectively, and with an organic matter content of 2.63%, and N 31.35 ppm, F 26.05 ppm, and P 1657.7 ppm. These determinations were made with a composite soil sample at a depth of 30 cm. The quality parameters of deep-well water for irrigation are as follows: pH 8.09, EC 4.14 dS·m^{-1}, SAR 2.58, and sodium concentration 19.31 meq·L^{-1}. All determinations were made according to methods established in the Official Mexican Standard [26].

2.2. Experimental Design and Treatment Arrangement

A randomized block design in a split-plot arrangement with three replicates was used. The large plots were for the saline water magnetic treatments: saline water from a deep well with magnetic treatment (MWT) using ionizing equipment, and non-magnetized water treatment (NMWT) located in parallel plots. The small plots were composed of ecotype 232098 and the San Gabriel and Estanzuela Ganador varieties of *L. corniculatus* L. Ecotype 232098 and the San Gabriel variety are both highly sensitive to soil salinity, whereas the Estanzuela Ganador variety is salinity tolerant, according to preliminary study reports carried out in the region under controlled shade net conditions [27,28]. The experimental unit (treatment) consisted of 3 plants per genotype at a distance 0.4 m between plants, placing three genotypes per water treatment (MWT and NMWT) in two rows of 3.6 m in length each, with independent irrigation from a pipe placed perpendicularly in order to provide MWT and NMWT irrigation (see Figure 1). Two plants were randomly selected per treatment to measure different variables, which were assessed from March 2023 to March 2024 under open field conditions.

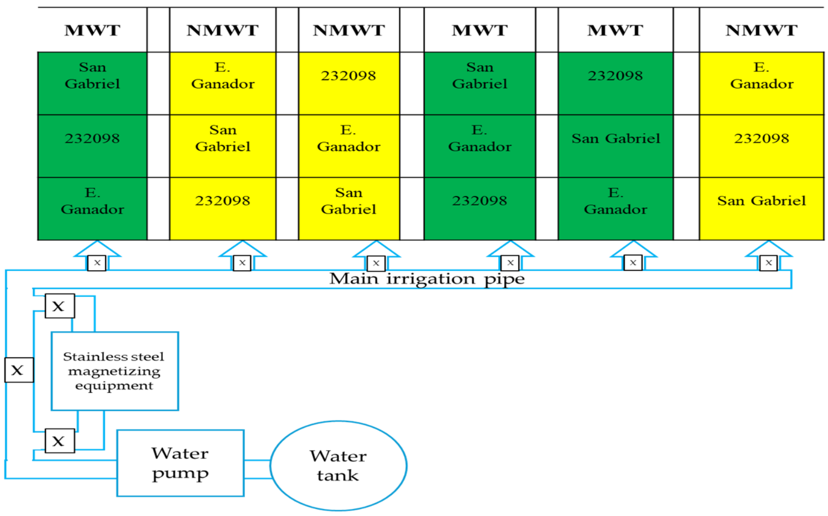

Figure 1. Distribution of treatments in a randomized block design in a split-plot arrangement in parallel plots. MWT is magnetized water treatment; NMWT is non-magnetized water treatment. E. Ganador is Estanzuela Ganador.

2.3. Irrigation System Setup

The experimental area was irrigated using a pressurized drip system at an optimum soil moisture content ranging from 24 to 30%, since 27% is the optimum water content according to the determinations made using the membrane pot method [29]. The field capacity (FC) was 27.2%, and the permanent wilting point (PWP) was 13.1%, which were determined at a depth of 30 cm that corresponds to the plant's rhizosphere area. The soil moisture content was measured at a depth of 30 cm in all plots on a real-time basis using a digital tensiometer (Model: MO750, Extech Instruments Co., Laredo, TX, USA).

The irrigation treatments were applied through the main irrigation line with 2″ polyvinyl chloride (PVC) conduits, with two perpendicular irrigation lines of 1/2″ hose per row. Irrigation supplies were controlled by on/off valves. A self-compensating dripper (Model: CHAPIN DRIP TAPE, JAIN Irrigation Inc., Watertown, NY, USA) was used, at a rate of 2 L h^{-1} provision to each plant, with a flow rate of 8000 cm^3 per irrigation per plant. When the soil moisture content reached the lower water content level (24%), irrigation was resumed until the upper water content level (30%) was reached. It took 4 h to increase the soil's water content from 24% to 30%. During the second half of spring, summer and fall, the clover was irrigated every 4 days, whereas during winter and the first half of spring, irrigation was applied every 15 days (Figure 1).

2.4. Magnetic Treatment of Saline Water

The main polyvinyl chloride conduit (PVC) pipe was connected to a cistern as a reservoir of saline water extracted from the deep well from whence the magnetically treated water was supplied. This treatment consisted of passing the saline water through stainless steel magnetizing equipment, model 608, brand STATERA Magnetics Industries 205 (Sin. MX). The magnetic device specifications are a diameter of 2″, Lorentz magnetizing force 14,700 Gauss, an exposure time of 3 min, and a flux rate of 4–6 L s^{-1}. The non-magnetized saline water was transported via a main PVC pipe directly from the cistern to the irrigation area. This untreated water registered an electrical conductivity (EC) of 2.8 dS m^{-1}, which was determined by chemical analysis before the establishment of the experiment (Figure 1).

2.5. Fertilization

In a standardized manner, during the experimental period and at least every four months, macro- and microelements were applied as nutritional materials for the adequate growth of the Lotus plants. In summer and fall, 20:40:00 Kg ha^{-1} of N, P and K, respectively, were applied in the form of dibasic ammonium phosphate. They were applied directly in the soil, along with the microelements Fe, Zn and B at a dose of 1 Kg ha^{-1} in diluted solution applied to foliage using a sprayer (Lola Safe 289020, SWISSMEX. Edo. De Mex. MX.). Xolocotzi-Acoltzi et al. [28] report that although *Lotus corniculatus* is a leguminous plant, it has a low nitrogen fixation capacity, with a level below the plant's requirement; thus, the fertilizer applied was the soluble foliar fertilizer NUTRICELL Amino 20-30-10 (HYDROCULTURA agricultura protegida, CDMX, MX).

2.6. Variables Measured

2.6.1. Climatic Conditions

A Davis Instruments model 6162 microclimatic station (Hayward, CA, USA), located 500 m from the experimental area, was used throughout the experiment to record the following: average, maximum, and minimum temperatures (°C); relative humidity (%); and average monthly and annual precipitation (mm).

2.6.2. Physicochemical Characteristics of Soil and Water

The following determinations were made for the soil: pH, electrical conductivity (EC, mS m^{-1}), total dissolved solids (ppm), sodium absorption ratio (SAR) and sodium content (Na, meq L^{-1}). Soil samples were collected from the plots using a 50 mm diameter probe inserted from 0 to 30 cm deep. Samples were collected by taking a composite sample from the three random sites of each plot and homogenized before analysis. These variables were measured at the beginning of the experiment (March 2023) and at the end of the first step of the experiment (March 2024).

2.6.3. Plant Growth and Yield

The variables measured were stem length (cm), rhizome crown width (cm), and plant cover (cm^2), using a ruler. Since the Lotus plant has a radial growth, plant cover was calculated using the circle area equation,

$$CV = \pi r^2$$

where CV is the cover plant and r is the radius of the foliar area.

In addition, the number of stems per rhizome, leaf area index (LAI), and fresh biomass production per rhizome (FBPR) (g) were measured. Stem length was measured from the base of the rhizome to the tip of the main stem, with measurements taken horizontally, diagonally or vertically, depending on the genotype's growth habit. The LAI was evaluated using an Accupar LP-80 ceptometer (Meter Group Inc., Pullman, WA, USA). The FBPR was measured by cutting stems 10 cm above the soil surface using Truper pruning shears, model 18,462 (China), and subsequently the fresh biomass was weighed in a Truper BASE-SEP digital scale (China). Data collection was performed every 45 days, with 2 cuts each in spring, summer, and autumn, and 1 cut in winter, for a total of 7 cuts per year. The average production of the two cuts per season was obtained, and only one measurement was made in the winter season. All measurements were performed for each treatment (Figure 2).

Figure 2. Growing of the *Lotus corniculatus* L. genotypes adapted to the study area in arid zones under open-field conditions.

2.6.4. Data Analysis

A variance analysis and Tukey's multiple range test with a p-value ≤ 0.05 [30] were performed on the database to identify the effects among treatments; in addition, principal component analysis (PCA) was performed using Minitab 16 and SAS Version 9.0 software. Excel V. 6.0 program was used to perform graphic analysis.

3. Results

3.1. Climatic Conditions

From March 2023 to March 2024, the total recorded annual rainfall was 196.4 mm, falling below the regional historical annual average of 258 mm [24]. The months with the highest rainfall were July and October, with 71.6 mm and 51 mm, respectively, and the maximum temperatures ranged from 3.6 to 39.7 °C (Figure 3).

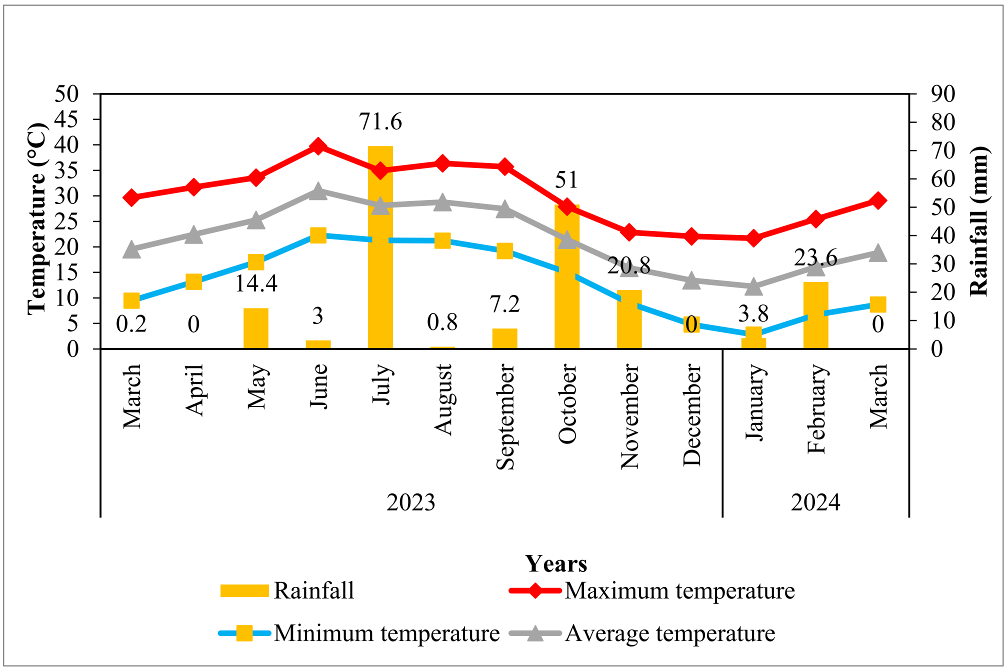

Figure 3. Rainfall, mean temperature, average maximum, and average minimum were recorded in the open-field experimental area from March 2023 to March 2024. Bermejillo, Dgo.

3.2. Water and Soil Salinity

The results of the chemical analysis of deep-well water conducted in 2023 were compared to the quality parameters, corresponding to the non-magnetized water treatment [(NMWT) (left column)] and the magnetized water treatment [(MWT) (right column)] (Table 1).

Table 1. Quality parameters of deep-well water used for agricultural irrigation.

Parameters	Non-Magnetized Water Treatment (NMWT) (20 July 2023)	Magnetized Water Treatment (MWT) (20 July 2023)
Hp	7.16	7.29
Electrical conductivity	2.46	2.631
Total dissolved solids (dS L^{-1})	1574.4	1683.84
Sodium adsorption ratio (SAR) (dS L^{-1})	4.71	4.01
Cations and anions		
Calcium (meq L^{-1})	12.61	14.50
Magnesium (meq L^{-1})	3.70	5.49
Sodium (meq L^{-1})	10.17	9.97

Table 1. *Cont.*

Parameters	Non-Magnetized Water Treatment (NMWT) (20 July 2023)	Magnetized Water Treatment (MWT) (20 July 2023)
Potassium (meq L^{-1})	0.18	0.25
Carbonates (meq L^{-1})	0.00	0.00
Bicarbonates (meq L^{-1})	3.20	3.20
Chlorides (meq L^{-1})	5.04	5.32
Sulfates (meq L^{-1})	18.25	20.58

Chemical analysis conducted at the Centro Nacional de Investigación Disciplinaria en Relaciones Agua Suelo Planta Atmosfera (CENID-RASPA) at the Instituto Nacional de Investigaciones Forestales Agrícolas y Pecuarias in Gómez Palacio, Dgo. Mexico. NMWT is non-magnetized water treatment, and MWT is magnetized water treatment.

Based on the soil chemical analysis, Table 2 compares the parameters pH, electrical conductivity (EC) (dS m^{-1}), total dissolved solids (ppm), sodium absorption ratio (SAR), and sodium concentration (meq L^{-1}), before setting up the experiment (left column), and after 1 year in the non-magnetized water treatment (middle column) and the magnetized water treatment (MWT).

Table 2. Soil chemical characteristics when watered at the beginning of the experiment (March 2024) and at the end of the experiment (March 2024) using the magnetized water treatment (MWT) and the non-magnetized water treatment (NMWT) in *Lotus corniculatus* L.

Chemical Parameters *	Before Setting Up the Experiment ** (March 2023)	NMWT MWT (March 2024)	
pH	8.1	8.0	8.1
Electrical conductivity (EC) (dS m^{-1})	4.14	7.2	5.8
Total dissolved solids (ppm)	-	5804	4636
Sodium absorption ratio (SAR)	2.58	8.4	6.2
Sodium concentration (meq L^{-1})	19.31	35.4	20.7

* Chemical analysis carried out at the Centro Nacional de Investigación Disciplinaria en Relaciones Agua Suelo Planta Atmosfera (CENID-RASPA) of the Instituto Nacional de Investigaciones Forestales Agrícolas y Pecuarias in Gómez Palacio, Dgo. Mexico. NMWT is non-magnetized water treatment, and MWT is a magnetized water treatment.—No available chemical analysis; ** soil not watered for more than 20 years, and before this time it was watered using catchment water in the high watershed of the Nazas Aguanaval, with water not contaminated with salts.

3.3. Plant GrowthT While During Winter the San Gabriel Variety Was the Most Affected, Going from 21 cm to 15.1 cm in MWT and NMWT, Respectively, Which Means 28.1% Lower Growth in Soils Irrigated with Water Without Magnetic Treatment (Figure 4)

The diameter of the rhizome at its basal part, called crown width, did not vary as a result of clover genotype or magnetized water treatment during the different seasons of the year (Figure 5).

As for the leaf area index, which refers to the development of the plant's foliage in relation to the area covered by soil, the Estanzuela Ganador variety recorded the best values of 3.2 and 3.3 in water without and with magnetic treatment, respectively, with no statistical difference between them; on the other hand, ecotype 232098 had the worst response in the same season and with both types of water, which means that the effect on both Lotus genetic materials was a genotype–environment interaction, as in the case of crown width, affecting ecotype 232098 more in the fall season compared to the Estanzuela Ganador variety (Figures 6 and 7).

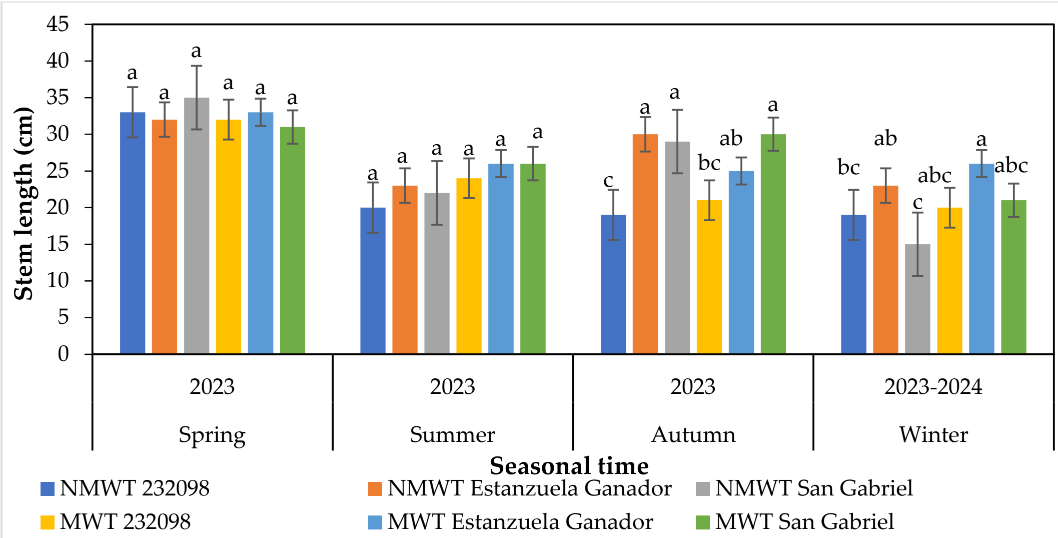

Figure 4. Effect of the magnetic treatment of saline water on the stem lengths (cm) of three genetic materials of forage clover (*Lotus corniculatus* L.) under open-field conditions in northern Mexico. Tukey test ($p \leq 0.05$). Columns with the same letters above them at each seasonal time are not different from each other. MWT is magnetized water treatment; NMWT is non-magnetized water treatment (control).

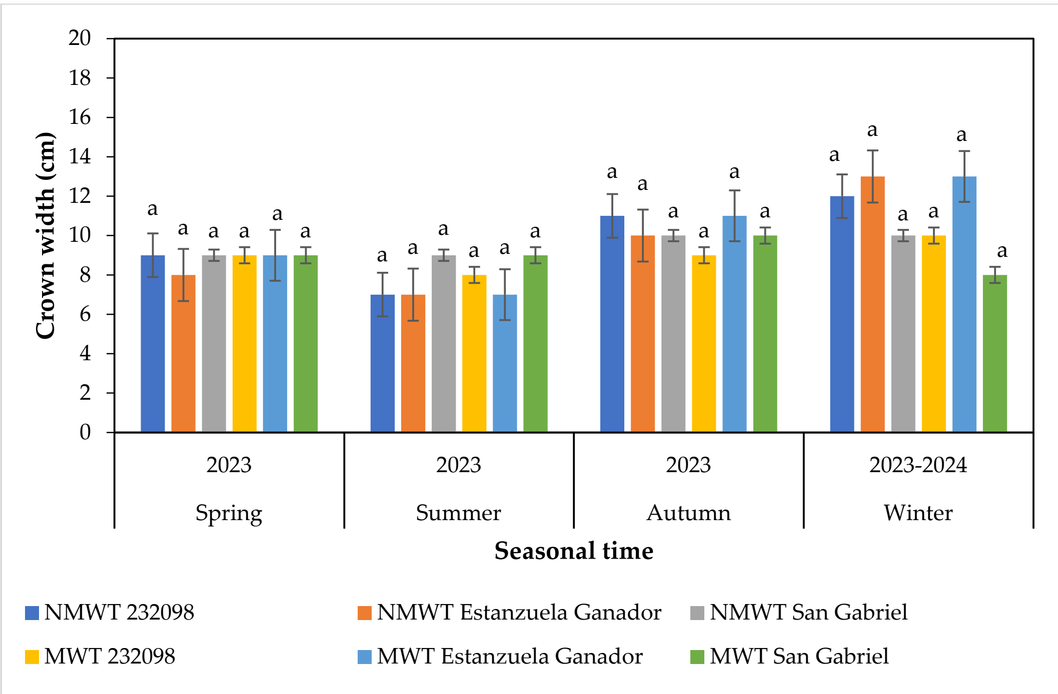

Figure 5. Magnetic treatment of saline water and its effect on crown width (cm) of three genetic materials of forage clover (*Lotus corniculatus* L.) under open-field conditions in northern Mexico. Tukey test ($p \leq 0.05$). Columns with the same letters above them at each seasonal time are not different from each other. MWT is magnetized water treatment; NMWT is non-magnetized water treatment (control).

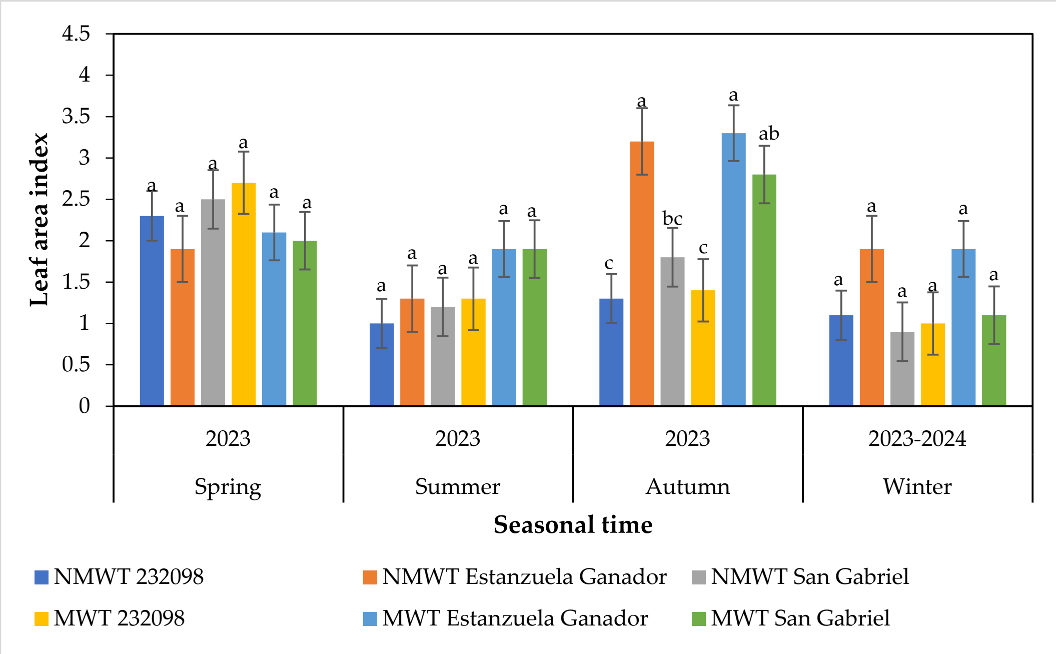

Figure 6. Magnetic treatment of saline water and its effect on the leaf area index of three genetic materials of forage clover (*Lotus corniculatus* L.) under open-field conditions in northern Mexico. Tukey test ($p \leq 0.05$). Columns with the same letters above them at each seasonal time are not different from each other. MWT is magnetized water treatment; NMWT is non-magnetized water treatment (control).

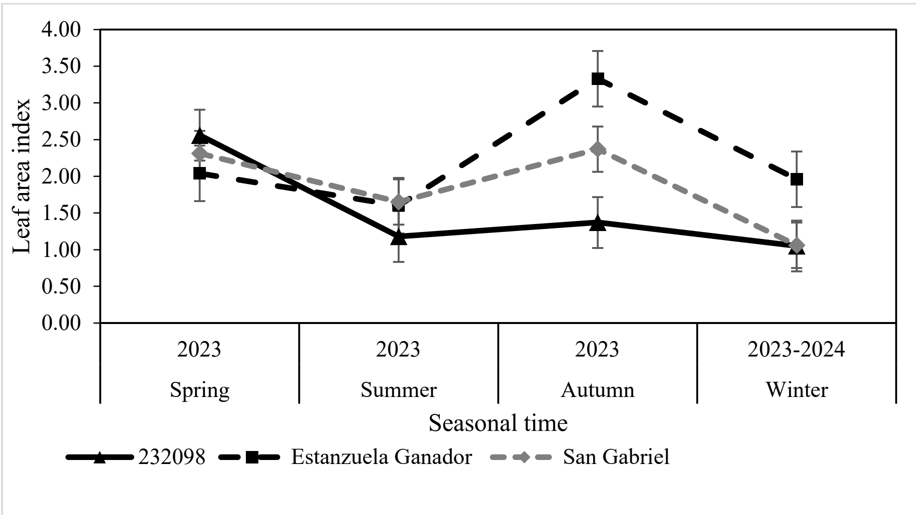

Figure 7. Behavior of the average leaf area index independent of water treatment (MWT and NMWT) in *Lotus corniculatus* genotypes in different seasons during 2023–2024.

Plant cover showed uniform behavior without significant differences between spring and summer seasons, and in fall, the Estanzuela Ganador and San Gabriel varieties had the highest coverage, with values of 2483.3 cm^2 and 2527.7 cm^2, without statistical difference ($p \leq 0.05$) between them; on the other hand, ecotype 232098 recorded the significantly lowest values of 1127.6 cm^2 and 941.7 cm^2 in non-magnetized water and magnetized water, respectively, without statistical difference (Figure 8).

The effect on the number of stems in the Lotus ecotype was seen from the start of the summer season, where the San Gabriel variety decreased its number of stems regardless of the type of water treatment. A similar trend was shown in the fall season, only with an additional negative effect in ecotype 232098 in MWT compared to NMWT (Figure 9).

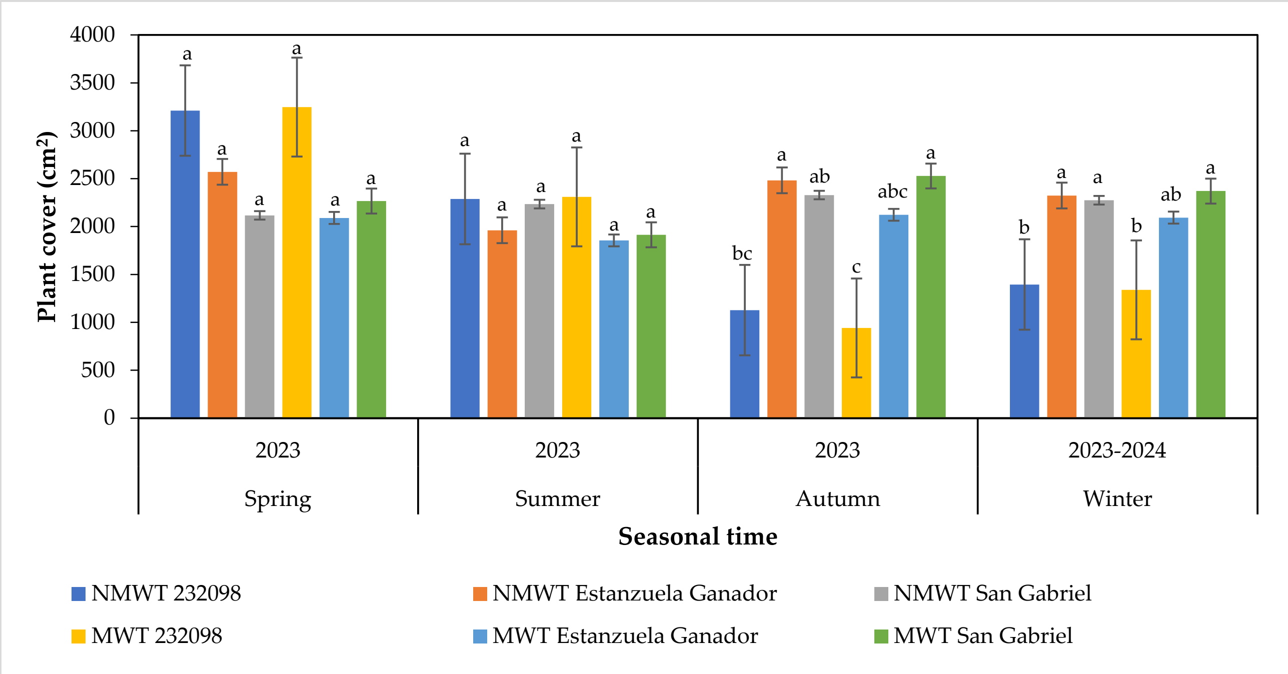

Figure 8. Magnetic treatment of saline water and its effect on the plant cover (cm) of three genetic materials of forage clover (*Lotus corniculatus* L.) under open-field conditions in northern Mexico. Figures with the same letters above a bar in the same season are statistically equal. MWT is magnetized water treatment; NMWT is non-magnetized water treatment (control).

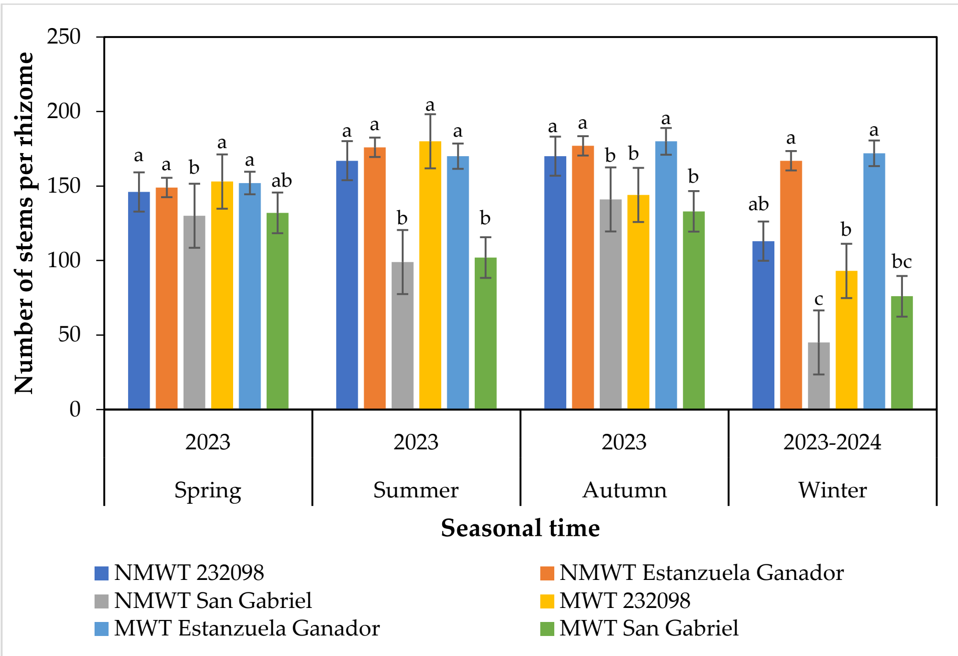

Figure 9. Magnetic treatment of saline water and its effect on the number of stems per rhizome of three genetic materials of forage clover (*Lotus corniculatus* L.) under open-field conditions in northern Mexico. Tukey test ($p \leq 0.05$). Figures with the same letters above a bar in the same year season are statistically equal. MWT is magnetized water treatment; NMWT is non-magnetized water treatment (control).

3.4. Forage Yield

Beginning in the fall, the Estanzuela Ganador and San Gabriel varieties showed significantly increased FBPR, regardless of water treatment type, MWT or NMWT, with values of 288.9 and 249.5 g and 184.2 and 247 g of FBPR, respectively. Ecotype 232098 showed the lowest response in both types of irrigation water in the fall, with values of 36 g and 53 g, respectively, without a statistical difference between them. Regardless of this, at the start of the experiment during the spring season, it showed the highest yield in terms of FBPR. In winter, the Estanzuela Ganador variety stood out in both types of water (Figures 10 and 11).

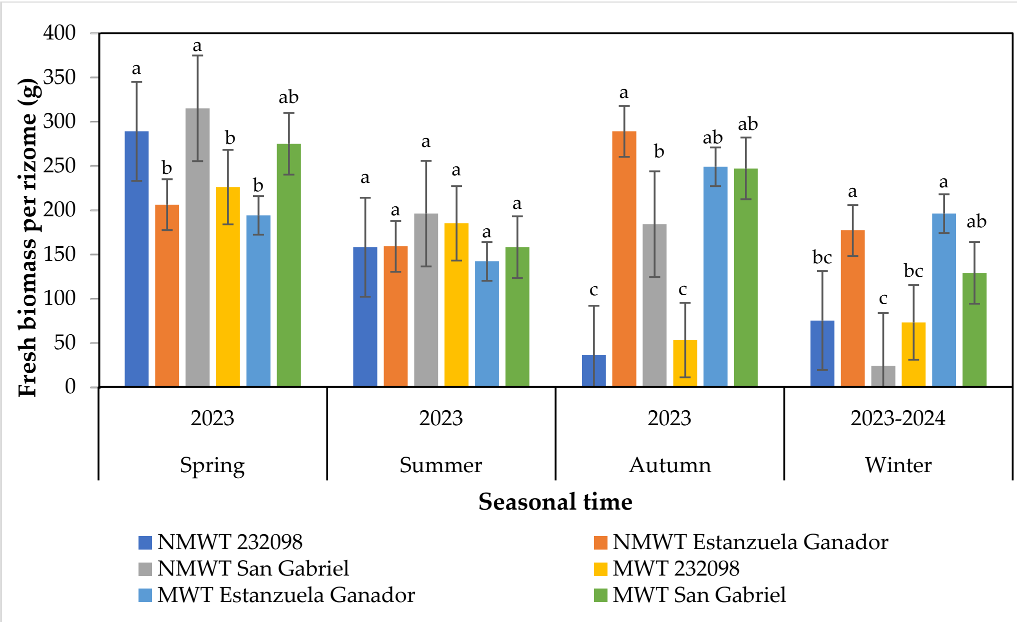

Figure 10. Magnetic treatment of saline water and its effect on the fresh weight (g) of three genetic materials of forage clover (*Lotus corniculatus* L.) under open-field conditions in northern Mexico. Tukey test ($p \leq 0.05$). Figures with the same letters above a bar in the same year season are statistically equal. MWT is magnetized water treatment; NMWT is non-magnetized water treatment (control).

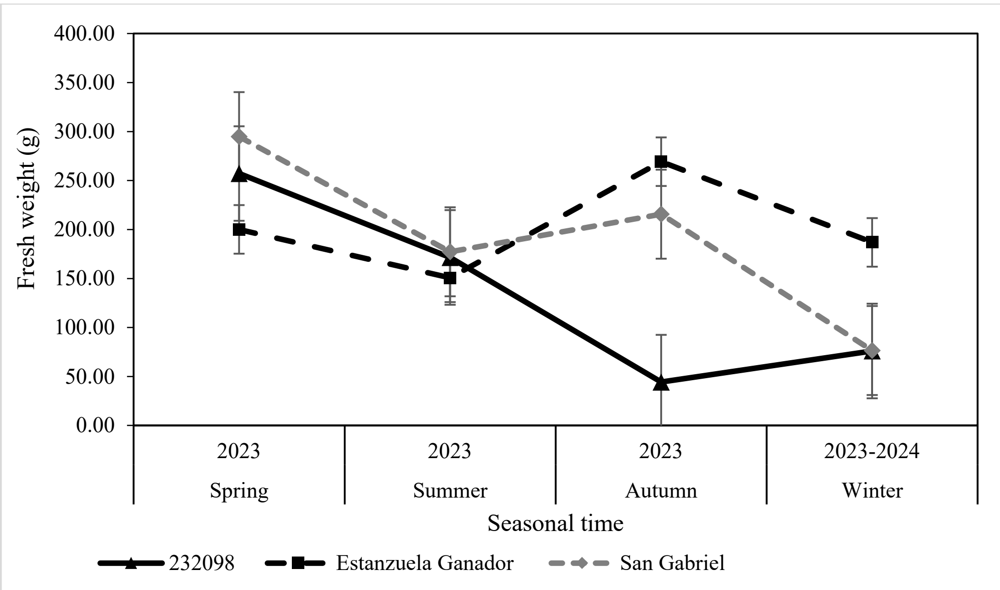

Figure 11. Fresh biomass production behavior of different genetic materials of *Lotus corniculatus* in different seasons of the year during 2023–2024.

3.5. Principal Component Analysis

According to the principal component analysis, PC1 shows positive loadings for most of the variables, indicating that it captures a general pattern of high positive correlations among them, except for crown diameter. In PC1, the variables stem length (0.544) and fresh biomass per rhizome (0.554) showed very similar positive contributions, while for PC2, the most positive loadings were crown diameter (0.632) and stem number (0.501), with a negative correlation of −0.430 with foliar area index. These results are associated with the structural attributes and architecture of Lotus genotypes (Table 3).

Table 3. Results of the Principal Components Analysis (PCA) showing the loading contributions of the different growth, physiological, and productivity variables in Lotus genotypes evaluated across different seasons under magnetic water treatment.

Variable	Loading Values in Two Principal Components	
	PC1	PC2
Stem length	0.544	−0.062
Crown diameter	−0.063	0.632-
Plant cover	0.434	0.375
Stem number	0.280	0.501
Foliar area index	0.355	−0.430
Fresh biomass per rhizome	0.554	−0.140

PC1 is the first principal component, while PC2 is the second principal component.

The PCA was performed to reduce the dimensionality of a data set comprising various morphological and physiological variables measured in Lotus genotypes. The first two principal components (PC1 and PC2) explain 90.0% of the variance (49.2% in PC1, and 40.7% in PC2) (Figure 12).

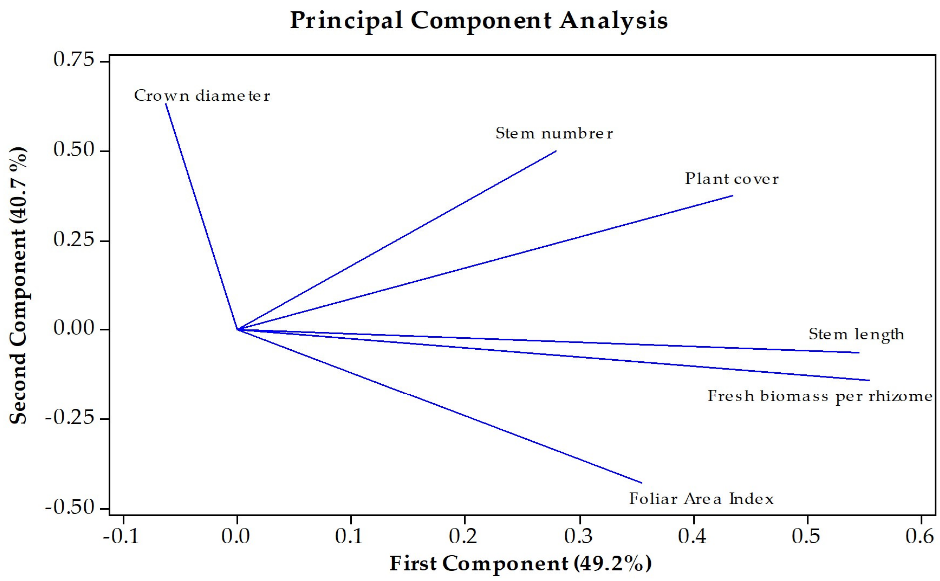

Figure 12. Distribution of variables—crown diameter, stem number, plant cover, stem length, fresh biomass per rhizome, and foliar area index—in the orthogonal plane defined by the first two principal components (PCs) extracted from 24 observations at four seasonal time points, with two water treatments and three *L. corniculatus* genotypes.

The PCA emphasizing genotypes, water treatments and seasons revealed distinct patterns of variation among the evaluated variables. The distribution of Lotus genotypes in the PCA plot primarily reflects seasonal patterns, indicating that genetic responses are more influenced by seasonal conditions than by specific genotypic performance. Regarding treatments, the diagram shows that NMWT is mainly associated with greater crown diameter, stem number, and plant cover, suggesting a positive influence of NMWT on structural traits. However, during fall, plant responses exhibited an opposite trend concerning water treatment, implying a possible interaction between seasonal factors and treatment efficacy (Figure 13).

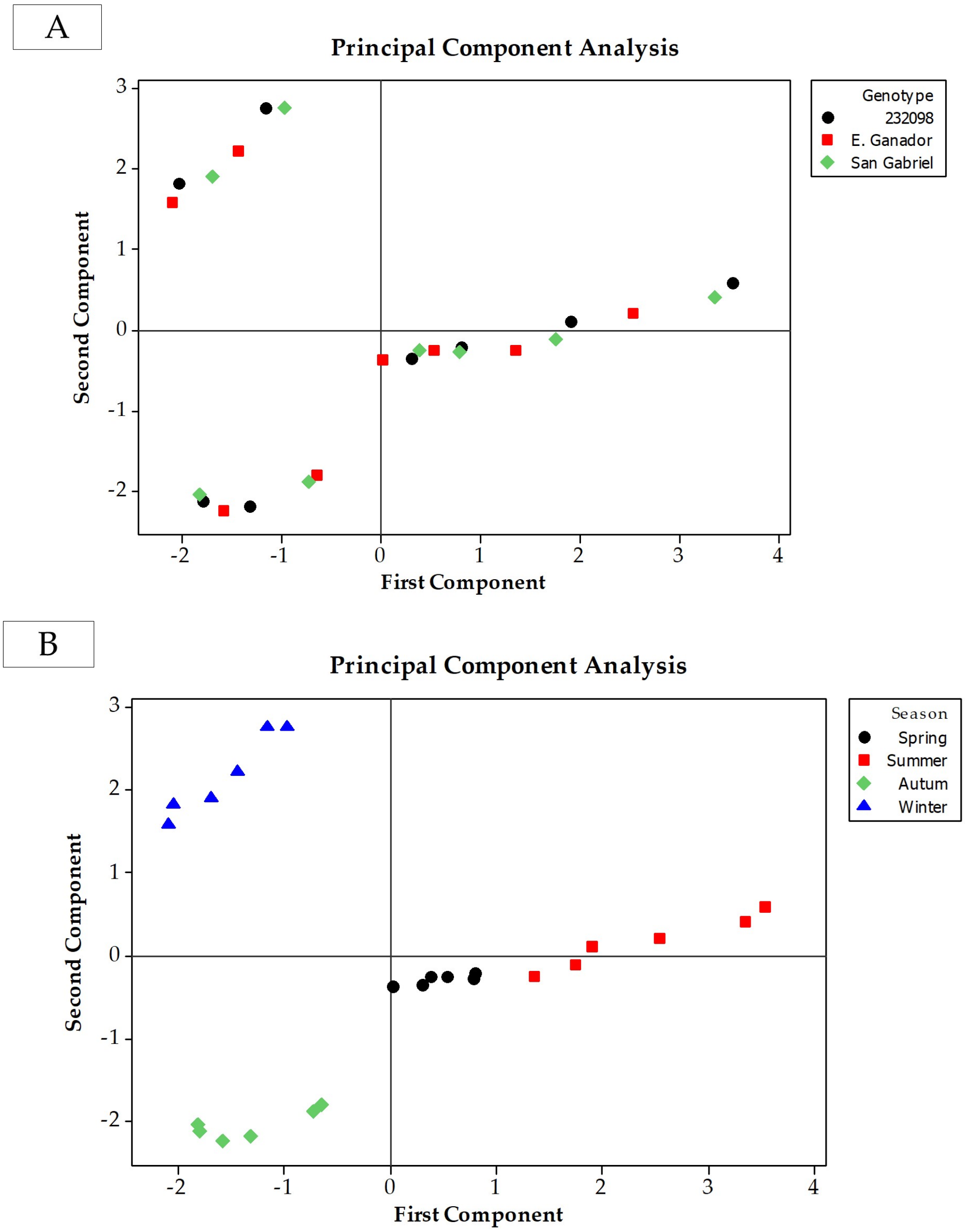

Figure 13. *Cont.*

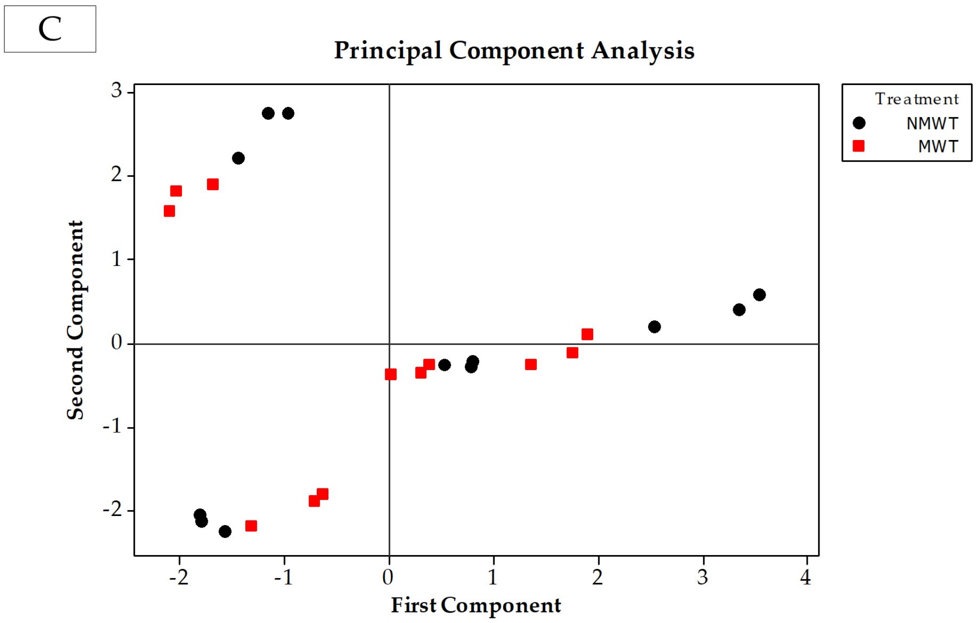

Figure 13. Distribution of 24 observations as part of the experimental area for (**A**) three *L. corniculatus* genotypes (San Gabriel and Estanzuela Ganador varieties plus one genotype with ID: 232098), (**B**) four seasonal times (spring, summer, fall, and winter), and (**C**) two magnetic water treatments (MWT, and NMWT) in the orthogonal plane defined by the two first principal components (PCs). MWT is magnetic water treatment; NMWT is no magnetic water treatment.

4. Discussion

The EC of deep-well water was 2.5 dS m^{-1}. This is close to the salinity limit allowed for agricultural use, 3 dS m^{-1}, based on the Official Mexican Standard NOM-127-SSA1-1994 [31], which represents a high risk of saline contamination in the soil due to salt accumulation over time. The initial EC in the soil at 40 cm deep was 4.14 dS m^{-1}, and after 1 year of watering the values increased to 7.2 and 5.8 dS m^{-1} in NMWT and MWT, respectively, with the salt accumulation being 19.4% less in MWT than in NMWT. These results are similar to the findings reported by Nessrien [32], who found that the rate of EC accumulation was lower from one year to the next when magnetized water was applied. Similar results were found in the sodium absorption ratio (SAR), with values from 8.4 to 6.2, and in exchangeable sodium (Na), with values from 35.34 to 20.7 Meq L^{-1} in NMWT and MWT, respectively, in comparison to the initial values in the soil content, which were 2.58 and 19.31 Meq L^{-1} for SAR and exchangeable sodium, respectively. The values increased in both water treatments, but less in MWT. Vladimir [33] reported a low increase in the rate of soil salinity accumulation when using magnetized water. This response is similar to those reported by Nessrien [32], Hamsa et al. [34] and Abdelghany et al. [35]. Thus, the mitigation of salt accumulation may be more evident in subsequent agricultural cycles.

In relation to the behavior of the Lotus plant's stem length, the results suggest an interaction effect between the genotype and the environment, depending on the seasonal time, with some genetic materials being more affected than others, except for the Estanzuela Ganador variety, which was more suitable in terms of its tolerance regardless of the type of water applied. The above suggests that the number of new stems per rhizome does not show high variation among Lotus genotypes, regardless of the magnetic treatment of the water used for irrigation across seasons. Liu et al. [36] reported the better growth of *Vitis vilifera* vine using magnetized water, and Omran [37] found improved germination, growth and salinity tolerance in cereal crops using the same treatment. As for rhizome diameter, it showed greater stability with the use of magnetically treated or untreated water, which suggests a tendency toward salinity tolerance in this variable.

The leaf area index results were stable during the four seasons of the year, with only a slight variation during fall. This coincides with the findings in the clover *L. corniculatus* reported by Pedroza-Sandoval et al. [19]. However, Yi et al. [14] reported greater stem width and a higher leaf area index in cotton when using magnetized water. This means that the response of this variable to magnetized water depends on the genetic material used, and the environmental and crop management conditions [38]. Plant cover showed uniform behavior with no significant statistical difference between Lotus genotypes or magnetic water treatment during the spring and summer seasons; in fall, the Estanzuela Ganador and San Gabriel varieties had the highest coverage, where the effect of salinity begins to be noticed from the third season of the year, possibly due to a cumulative effect of salts in the soil [33]. The winter responses of the San Gabriel and Estanzuela Ganador varieties in terms of the number of stems per rhizome had values of 60.5 and 169.5, respectively, but there was only 15.3% more fresh biomass in Estanzuela Ganador compared to the San Gabriel variety, which is related to the fact that the latter has greater stem length and foliage density, especially in winter, because it is more tolerant to cold, with a compensatory effect on the low number of stems per rhizome.

The fresh biomass yield per rhizome suffered no effect due to the magnetic water treatment, but there was a variation in the response of this variable among Lotus genotypes, mainly in the spring and autumn seasons. The Estanzuela Ganador and San Gabriel varieties showed the best response, while ecotype 232098 showed the worst response in the winter season. This response suggests that the effect is due to the genotype, rather than the environment or the interaction of both, according to the principles of universal genetics, which establish that the phenotype is the result of genotype, environment and genotype–environment interaction [39,40]. In contrast, Zhou et al. [41] reported that magnetized irrigation water increased cotton yields and provided a more efficient use of water.

This response is associated with genotype, rather than an environmental effect or genotype–environment interaction response, which coincides with the effects found in this study on the variables stem thickness, leaf area index and plant cover, which are the main biological parameters associated with forage production in terms of fresh biomass per rhizome of the Lotus plant. Although the 7.2 dS m^{-1} value of EC in the soil after one year of irrigation with saline water did not affect the fresh biomass yield, this is explained by the fact that the soil salinization process occurs gradually, so the value reached at the end of the year did not affect this variable. This is consistent with what was reported by Abedingpour and Rohani [42], Hamza et al. [34], Abdelghany et al. [35] and Wang et al. [43], who showed that a negative effect on crops occurs with the use of saline water over the years, through a process of gradual salt accumulation in the soil. The Estanzuela Ganador variety was the most stable against the seasonal effect and salinity, while the most sensitive to both effects was ecotype 232098, which confirms that the environmental effect is dependent on the genotype, as cited by Napier et al. [40] and Pedroza-Sandoval et al. [27].

The highlights of the principal component analysis are the differential contribution of variables to the overall variation. Variables such as plant cover, fresh biomass per rhizome, and foliar area index are positively aligned along PC1, showing their association with productivity-related attributes. Meanwhile, crown diameter contributes predominantly to PC2, which relates to the structural characteristics of the genotypes. Overall, the separation of variables between PC1 and PC2 suggests that the measured traits can be broadly categorized into productivity-related traits (PC1) and structural or architectural traits (PC2). This differentiation is valuable for selecting genotypes with desirable attributes, whether the focus is on maximizing biomass production or optimizing structural characteristics for these specific agricultural or environmental conditions [44].

Overall, the results indicate that seasonal genetic background is the primary driver of variation in this study, with treatment playing a secondary role. These results suggest that cover size may be a critical factor for optimizing plant performance [45], although further studies are needed to elucidate the underlying causal mechanisms.

Finally, all these findings indicate that the magnetic treatment of saline water has a low effect in the short term on the forage *Lotus corniculatus* L. The effect of inhibiting the rate of salt accumulation in the soil caused by irrigation with magnetized water over time can be exploited to mitigate the negative impacts on areas irrigated with saline water extracted from overexploited aquifers. This variable only varied between genetic materials, with the Estanzuela Ganador and San Gabriel varieties being the best options for clover production in the region under open field conditions in arid zones with extreme climates, with a better response in the case of the Estanzuela Ganador variety throughout the year.

5. Conclusions

Magnetized water inhibits the rate of salt accumulation in the soil after one year of irrigation with saline water. The response of Lotus genotypes to salt accumulation in the soil began during the second season (summer), but was more noteworthy during the fall and winter seasons, possibly associated with a process of salt accumulation in the soil throughout the year as a result of irrigation with saline water from a deep well. Although some agronomic variables such as leaf area index, plant cover and stem length were slightly affected by the magnetic water treatment, due to a lower rate of salt accumulation in the soil from the third season onwards, fresh biomass production was not affected. The greatest effect on fresh biomass was obtained in the Estanzuela Ganador variety, with an outstanding tolerance response to soil salinity and year seasonality. Genotype 232098 showed the lowest response to water treatment in its different growth, development and forage production variables at the end of the year; the San Gabriel variety showed a median response. The inhibitory effect of salt accumulation in the soil due to irrigation with magnetized water is gradual, so in the year of evaluation, it only showed a positive effect on some agronomic variables, but not on fresh biomass yield as a final variable of forage production.

Author Contributions: Conceptualization: A.P.-S., L.Á.G.-E. and M.d.R.J.-S.; methodology: A.P.-S., L.Á.G.-E. and I.G.-Á.; software: A.P.-S., M.d.R.J.-S. and J.A.M.-R.; validation: A.P.-S. and L.Á.G.-E.; formal analysis: A.P.-S. and I.G.-Á. investigation: A.P.-S., I.G.-Á. and J.A.M.-R.; resources: A.P.-S.; data curation: A.P.-S. and I.G.-Á.; writing—original draft preparation: A.P.-S.; writing—review and editing: L.Á.G.-E. and M.d.R.J.-S.; visualization: L.Á.G.-E. and M.d.R.J.-S.; supervision: A.P.-S. and I.G.-Á.; project administration: A.P.-S.; funding acquisition: A.P.-S. All authors have read and agreed to the published version of the manuscript.

Funding: This study was supported by Dirección General de Investigación y Posgrado—Universidad Autónoma Chapingo through project ID: 24022-EI.

Data Availability Statement: The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding authors.

Acknowledgments: The authors acknowledge Joel Burgueño Aguirre for his support as a technician in establishing the experimental area and recording the field data. In addition, thanks go to the Water Soil Plant and Atmosphere Laboratory of the National Institute of Forestry, Agricultural and Livestock Research for the soil, and water chemical analysis.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. INECC-CGACC. México Ante el Cambio Climático. 2018. Available online: https://cambioclimatico.gob.mx/impactos-del-cambio-climatico-en-mexico/ (accessed on 11 August 2024).
2. Karolina, F.; Agnieszka, W. The impact of extreme weather events as a consequence of climate change on the soil moisture and on the quality of the soil environment and agriculture—A review. *Catena* **2023**, *231*, 107378.
3. Judit, D. From mystery to reality: Magnetized water to tackle the challenges of climate change and for cleaner agricultural production. *J. Clean. Prod.* **2023**, *425*, 139077.
4. Azpilcueta-Pérez, M.E.; Pedroza-Sandoval, A.; Trejo-Calzada, R.; Sánchez-Cohen, I.; Jacobo-Salcedo, M.D.R. Chemical residuality in maize (*Zea mays* L.) fields irrigated with deep well water. *Rev. Ecosist. Y Recur. Agropecu.* **2018**, *5*, 111–117. [CrossRef]
5. Macías, M.A.; Sevilla, G.Y.L. Naturaleza vulnerada. Cuatro décadas de agricultura industrializada de frutas y hortalizas en el sur de Jalisco, México (1980–2020). *Rev. Cienc. Soc. Y Humanid.* **2021**, *8*, 64–91. [CrossRef]
6. EOS DATA ANALYTICS. Salinidad Del Suelo: Cómo Prevenirla y Reducirla. 2024. Available online: https://eos.com/es/blog/salinidad-del-suelo/ (accessed on 6 October 2024).
7. Okba, S.K.; Mazrou, Y.; Mikhael, G.B.; Farag, M.E.H.; Alam-Eldein, S.M. Magnetized Water and Proline to Boost the Growth, Productivity and Fruit Quality of 'Taifi' Pomegranate Subjected to Deficit Irrigation in Saline Clay Soils of Semi-Arid Egypt. *Horticulturae* **2022**, *8*, 564. [CrossRef]
8. Zúñiga, O.; Benavides, J.A.; Ospina-Salazar, D.I.; Jiménez, C.O.; Gutiérrez, M.A. Magnetic treatment of irrigation water and seeds in agriculture. *Ing. Y Compet.* **2016**, *18*, 217–232.
9. Ali, Y.; Samaneh, R.; Kavakebian, F. Applications of Magnetic Water Technology in Farming and Agriculture Development: A Review of Recent Advances. *Curr. World Environ.* **2014**, *9*, 695–703. [CrossRef]
10. Ahmed, A.M.; Al-Ogaidi, A.A.; Wayayok, A.; Rowshon, M.K.; Abdullah, A.F. The influence of magnetized water on soil water dynamics under drip irrigation systems. *Agric. Water Manag.* **2017**, *180*, 70–77. [CrossRef]
11. Alfonso, I.; Daniel Pérez, G.C.; Pérez, M.I.; Silveira, P.E.A. Efecto del agua tratada magnéticamente sobre los procesos biológicos. *Rev. Electrón. Vet.* **2009**, *10*, 1–20. Available online: https://www.redalyc.org/articulo.oa?id=63611961010 (accessed on 10 July 2024).
12. Alattar, E.; Radwan, E.; Elwasife, K. Improvement in growth of plants under the effect of magnetized water. *AIMS Biophys.* **2022**, *9*, 346–387. [CrossRef]
13. Mamani, A.F. *Aplicación de Agua Magnetizada para la Producción de Papa (Solanum tuberosum L.) en la Estación Experimental de Patacamaya*; SIDALC: La Paz, Bolivia, 2017. Available online: https://repositorioslatinoamericanos.uchile.cl/handle/2250/1174059 (accessed on 15 November 2024).
14. Yi, G.; Wang, Q.; Wang, K.; Zhang, J.; Wei, K.; Liu, Y. Spring irrigation with magnetized water affects soil water-salt distribution, emergence, growth, and photosynthetic characteristics of cotton seedlings in Southern Xinjiang, China. *BMC Plant Biol.* **2023**, *23*, 174. [CrossRef] [PubMed]
15. Sifuentes-Rodríguez, N.S.; Pedroza-Sandoval, A.; Zegbe, J.A.; Trejo-Calzada, R. Indicadores de productividad y calidad de gel de sábila en condiciones de estrés salino. *Rev. Fitotec. Mex.* **2020**, *43*, 181–187. [CrossRef]
16. Mota-Ituarte, M.; Pedroza-Sandoval, A.; Minjares-Fuentes, R.; Trejo-Calzada, R.; Zegbe, J.A.; Quezada-Rivera, J.J. Water deficit and salinity modify some morphometric, physiological, and productive attributes of *Aloe vera* (L.). *Bot. Sci.* **2023**, *101*, 463–475. [CrossRef]
17. Fortis-H, M.; y Rhodante, A. Naturaleza y Extensión del Mercado de Agua en el Distrito de Riego 017 de la Comarca Lagunera, México. In *Instituto Internacional de Manejo del Agua IWMI*; Serie Latinoamericana No. 10; Instituto Internacional del Manejo del: Agua México, Mexico, 1999; p. 71. Available online: https://www.iwmi.org/Publications/Latin_American_Series/pdf/10.pdf (accessed on 5 June 2024).
18. González-Espíndola, L.A.; Pedroza-Sandoval, A.; de los Santos, G.G.; Trejo-Calzada, R.; Álvarez-Vázquez, P.; María del Rosario Jacobo-Salcedo, M. Secondary Metabolites and Their Antioxidant Activity Enhance the Tolerance to Water Deficit on Clover Lotus corniculatus L. through Different Seasonal Times. *Int. J. Plant Biol.* **2024**, *15*, 175–186. [CrossRef]
19. Pedroza-Sandoval, A.; Xolocotzi-Acoltzi, S.; Trejo-Calzada, R.; García-De los Santos, G.; Álvarez-Vázquez, P.; Arreola-Ávila, J.G. Leaf area index and forage productivity indicators of *Lotus corniculatus* L. at different soil moisture contents and seasons of the year. *Rev. Mex. Cienc. Pecu.* **2024**, *15*, 17–31.
20. Morris, P.; Carter, E.B.; Hauck, B.; Lanot, A.; Allison, G. Responses of L. corniculatus to environmental change 3: The sensitivity of phenolic accumulation to growth temperature and light intensity and effects on tissue digestibility. *Planta* **2021**, *253*, 35. [CrossRef]
21. Santacoloma-Varón, L.E.; Granados-Moreno, J.E.; Aguirre-Forero, S.E. Evaluación de variables agronómicas, calidad del forraje y contenido de taninos condensados de la leguminosa *Lotus corniculatus* en respuesta a biofertilizante y fertilización química en condiciones agroecológicas de trópico alto andino colombiano. *Entramado* **2017**, *13*, 222–233. [CrossRef]

22. Pedroza-Parga, E.; Pedroza-Sandoval, A.; Velasquez-Valle, M.A.; Sánchez-Cohen, I.; Samaniego-Gaxiola, J.A. Effect of soil cover on the growth and productivity of buffel grass (*Cenchrus ciliaris* L.) in degraded soils of arid zones. *Rev. Mex. Cienc. Pecu.* **2022**, *13*, 866–878. [CrossRef]
23. Rojas, C.J.M. *Los Beneficios del Riego por Goteo en Tiempos de Sequía*; CIMMYT. Desarrollo Estratégico: El Batan, Mexico, 2021. Available online: https://idp.cimmyt.org/los-beneficios-del-riego-por-goteo-en-tiempos-se-sequia/ (accessed on 7 July 2024).
24. Medina-García, G.; Díaz-Padilla, G.; López-Hernández, J.; Ruiz-Corral, J.A.; Marín-Silva, M. *Estadísticas Climatológicas Básicas del Estado de Durango. (Periodo 1961–2003)*; Libro Técnico № 1; Campo Experimental Valle del Guadiana. Centro de Investigación Regional Norte Centro-Instituto Nacional de Investigaciones Forestales, Agrícolas y Pecuarias: Durango, Mexico, 2005; p. 240.
25. Bouyoucos, G.J. Hydrometer method improved for making particle size analysis of soils. *Agron. J.* **1962**, *54*, 464–465. [CrossRef]
26. NOM-021-RECNAT-2000; Norma Oficial Mexicana. Que Establece las Especificaciones de Fertilidad, Salinidad y Clasificación de Suelos. Estudios, Muestreo y Análisis. 2002. DOF. 31/12/2002. Available online: https://www.ordenjuridico.gob.mx/Documentos/Federal/wo69255.pdf (accessed on 1 November 2024).
27. Pedroza-Sandoval, A.; Trejo-Calzada, R.; Sánchez-Cohen, I.; Yáñez-Chávez, J.A.; Cruz-Martínez, A.; Figueroa-Viramontes, U. Water harvesting and soil water retention for forage production in degraded areas in arid lands of Mexico. In *New Perspectives in Forage Crops*; Ricardo, L.E., Leilson, R.B., Eds.; IntechOpen: London, UK, 2018; p. 210.
28. Xolocotzi-Acoltzi, S.; Pedroza-Sandoval, A.; García-De los Santos, G.; Álvarez-Vázquez, P.; Gramillo-Ávila, I. Growth, Productivity, Yield Components and Seasonality of Different Genotypes of Forage Clover *Lotus corniculatus* L. under Varied Soil Moisture Contents. *Plants* **2024**, *13*, 1407. [CrossRef] [PubMed]
29. Richards, L.A. Porous plate apparatus for measuring moisture retention and transmission by soil. *Soil Sci.* **1948**, *66*, 105–110. [CrossRef]
30. Fallas, J. Análisis de Varianza Comparando Tres o Más Medias. 2012. Available online: https://www.ucipfg.com/Repositorio/MGAP/MGAP-05/BLOQUE-ACADEMICO/Unidad-2/complementarias/analisis_de_varianza_2012.pdf (accessed on 1 October 2024).
31. Secretaria de Gobernación DOF. NORMA Oficial Mexicana NOM-127-SSA1-2021, Agua Para Uso y Consumo Humano. Límites Permisibles De La Calidad Del Agua. 2022. Available online: https://aneas.com.mx/wp-content/pdf/documentos-oficiales/11-lineamientos%20NOM-127-SSA1-2021.pdf (accessed on 8 December 2024).
32. Nessrien, S.A.K. Evaluation of Magnetizing Irrigation Water Impacts on the Enhancement of Yield and Water Productivity for Some Crops. *J. Agric. Sci. Technol.* **2018**, *A8*, 274–286.
33. Zlotopolski, V. The Impact of magnetic water treatment on salt distribution in a large unsaturated soil column. *Int. Soil Water Conserv. Res.* **2017**, *5*, 253–257. [CrossRef]
34. Hamza, A.H.; Sherif, M.A.; Wael, A.; Abd El-A, M.M. Impacts of Magnetic Field Treatment on Water Quality for Irrigation, Soil Properties and Maize Yield. *J. Mod. Res.* **2021**, *3*, 51–61. [CrossRef]
35. Abdelghany, A.E.; Abdo, A.I.; Alashram, M.G.; Eltohamy, K.M.; Li, J.; Xiang, Y.; Zhang, F. Magnetized Saline Water Irrigation Enhances Soil Chemical and Physical Properties. *Water* **2022**, *14*, 4048. [CrossRef]
36. Liu, X.; Wang, L.; Wei, Y.; Zhang, Z.; Zhu, H.; Kong, L.; Meng, S.; Song, C.; Wang, H.; Ma, F. Irrigation with magnetically treated saline water influences the growth and photosynthetic capability of *Vitis vinifera* L. *seedlings. Sci. Hortic.* **2020**, *262*, 109056. [CrossRef]
37. Omran, W.M.; Mansour, M.M.F.; Fayez, K.A. Magnetized water improved germination, growth and tolerance to salinity of cereal crops. *Int. J. Adv. Res.* **2014**, *2*, 301–308.
38. Kramina, T.E.; Meschersky, I.G.; Degtjareva, G.V.; Samigullin, T.H.; Belokon, Y.S.; Schanzer, I.A. Genetic variation in the *Lotus corniculatus* complex (Fabaceae) in northern Eurasia as inferred from nuclear microsatellites and plastid trnL-trnF sequences. *Bot. J. Linn. Soc.* **2018**, *188*, 87–116. [CrossRef]
39. Napier, J.D.; Heckman, R.W.; Juenger, T.E. Gene-by-environment interactions in plants: Molecular mechanisms, environmental drivers, and adaptive plasticity. *Plant Cell* **2023**, *35*, 109–124. [CrossRef]
40. Baye, T.M.; Abebe, T.; Wilke, R.A. Genotype-environment interactions and their translational implications. *Pers. Med.* **2011**, *8*, 59–70. [CrossRef]
41. Zhou, B.; Yang, L.; Chen, X.; Ye, S.; Peng, Y.; Liang, C. Effect of magnetic water irrigation on the improvement of salinized soil and cotton growth in Xinjiang. *Agric. Water Manag.* **2021**, *248*, 106784. [CrossRef]
42. Abedinpour, M.; Rohani, E. Effects of magnetized water application on soil and maize growth indices under different amounts of salt in the water. *J. Water Reuse Desalin.* **2017**, *7*, 319–325. [CrossRef]
43. Wang, D.; Zhang, L.; Zhang, J.; Li, W.; Li, H.; Liang, Y.; Han, Y.; Luo, P.; Wang, Z. Effect of Magnetized BrackishWater Drip Irrigation on Water and Salt Transport Characteristics of Sandy Soil in Southern Xinjiang, China. *Water* **2023**, *15*, 577. [CrossRef]

44. Ferreira, F.M.; do Amaral Santos de Carvalho Rocha, J.R.; Bhering, L.L.; Fernandes, F.D.; da Silva Lédo, F.J.; de Albuquerque Rangel, J.H.; Kopp, M.; Marinho, C.T.M.; Ribeiro da Silva, V.O.; Campolina, M.J. Optimal harvest number and genotypic evaluation of total dry biomass, stability, and adaptability of elephant grass clones for bioenergy purposes. *Biomass Bioenergy* **2021**, *149*, 106104. [CrossRef]
45. Koudahe, K.; Allen, C.S.; Koffi, D. Critical review of the impact of cover crops on soil properties. *Int. Soil Water Conserv. Res.* **2022**, *10*, 343–354. [CrossRef]