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Research article

Changes in Selected Chemical Properties of Karbala and Jalawla Sands during Cultivation under a Sandponics System

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ABSTRACT

This plant-house experiment compared temporal changes in selected chemical properties of Karbala and Jalawla sands cultivated under a Sandponics system. Six independent growing basins were used, with three replicate basins for each sand type. Each basin contained 15 red cabbage, 15 chard, and 15 lettuce plants, and sand samples were collected separately from every basin before and after cultivation. The measured properties were pH, electrical conductivity (EC), alkali-extractable silica (SiO_2), and KCl-extractable mineral nitrogen. Karbala sand showed a decrease of 1.067 pH units, from 6.360 to 5.293 [$t(2) = 160.000$, $p < 0.001$], whereas Jalawla sand decreased by 0.763 pH units, from 6.000 to 5.237 [$t(2) = 22.564$, $p = 0.002$]. EC decreased by 80.349% in Karbala sand and 87.919% in Jalawla sand. Alkali-extractable SiO_2 decreased by 20.557% and 20.690%, respectively. KCl-extractable mineral nitrogen decreased by 11.992% in Karbala sand [$t(2) = 13.536$, $p = 0.005$] and by 5.515% in Jalawla sand; however, the paired t-value for Jalawla was not estimable because the paired differences were identical across the three basins. The large EC decrease may indicate salt leaching, whereas decreases in pH, mineral nitrogen, and alkali-extractable silica require cautious interpretation as possible consequences of acidification, plant uptake, leaching, or mineral transformation. Because no untreated control was included, the observed changes cannot be attributed exclusively to the Sandponics system.

1. Introduction

Modern agricultural technologies are among the most important means used to improve soil properties and increase its productivity (Subramanian et al., 2025), especially in arid and semi-arid regions that suffer from low fertility of sandy soils, such as most agricultural environments in Iraq. Among these modern technologies, the Sandponics technique has emerged, which is considered an integrated agricultural system that relies on the use of sand as a growing medium for plants, with the recycling of water and nutrients. The sand acts as a biological and chemical filter that contributes to improving the quality of water and soil simultaneously (Sewilam et al., 2022; Baba & Ikeguchi, 2015). Sandponics technology relies on the integration of a sandy medium and nutrient solutions. The sand absorbs nutrients and regulates their availability to the plant, in addition to modifying some of the soil's physical and chemical properties, such as pH and electrical conductivity EC. This creates a balanced growing environment that improves nutrient availability for plants (Schreinemachers et al., 2018; Makokha et al.,

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2019). Meanwhile, the importance of sand selection with low salt and carbonate content cannot be overemphasized as it preserves a neutral pH and reduces salinity in the growth substrate (Sewilam et al., 2022).

The use of sandy substrates can be highly effective because it can lead to dramatic changes in sand chemistry. Investigations have shown that the mixing of sand with additives can lead to changes in pH, conductivity, porosity, and nutrient retention due to modifications in the movement of ions and the flow of water through the pore space (Zhang et al., 2019; Li et al., 2020). Nitrogen content is particular importance when it comes to sandy substrates as fast drainage could lead to nutrient losses while plant absorption and biological changes can lead to changes in the stock of mineral nitrogen (Nair et al., 2024). Changes in acidity and biological activity can also have an effect on the amount of alkali-extractable silica due to the processes of dissolution, leaching, or changes in poorly crystalline silicate forms (Wang et al., 2021). Thus, the present research used the data on pH, EC, alkali-extractable silica, and KCl-extractable mineral nitrogen since these variables denote the sand activity, salinity status, the well-defined silica fraction, and the amount of readily available mineral nitrogen. The study hypothesized that these properties would change during cultivation under the Sandponics system and that the magnitude of change would differ between Karbala and Jalawla sands because of their initial characteristics. The primary objective was to compare the responses of the two sands under the same cultivation system, rather than to compare Sandponics with a conventional cultivation method.

2. Materials and Methods

2.1 Experimental location

A plant-house experiment was conducted at the College of Education for Pure Sciences, University of Diyala, during the winter season from 1 November 2024 to 30 March 2025. Two collected sandy materials were evaluated: Karbala sand from the Al-Kabashi area and Jalawla sand collected near the Diyala Springs factory. The experiment comprised six independent growing basins, with three replicate basins for each sand type. Sand samples were collected separately from each basin before cultivation and again from the same basin after cultivation at a depth of up to 30 cm. Thus, each sand type was represented by three independent paired basin-level observations ($n = 3$). Laboratory analyses were conducted at the College of Agriculture, University of Baghdad.

2.2 Experiment design

2.2.1 Fish farming unit

The system included two fish tanks, each measuring 2 m × 3 m × 0.75 m, with a volume of approximately 4,500 L. Each tank was stocked with 150 common carp with an initial individual weight of 100–125 g, corresponding to an estimated initial biomass of 15.0–18.75 kg per tank. One fish tank supplied water to the three replicate basins assigned to one sand type. Fish in each tank received 400 g of feed per day, divided into two equal meals. The tanks were equipped with aeration pumps and a drainage system, and solar power was used to maintain continuous aeration.

2.2.2 Agriculture unit

Six independent growing basins were used: three containing Karbala sand and three containing Jalawla sand. Each basin measured 1.5 m × 3 m and was 0.5 m deep and contained 45 plants: 15 red cabbage plants, 15 chard plants, and 15 lettuce plants. The experiment therefore included 135 plants per sand type and 270 plants in total. The three plant species were co-cultivated within each basin; consequently, plant species was not treated as an independent factor in the analysis of basin-level sand

chemistry. Irrigation water from the fish tanks was distributed through perforated PVC pipes (16–20 mm diameter) arranged in a U-shape. The pipes were covered with gauze to reduce clogging. Water passed through the sand, was collected, and was then returned to the corresponding fish tank.

2.2.3 System operation, feeding, irrigation, and plant-house conditions

Before fish introduction, water was circulated through the system without fish for at least two weeks. Common carp were introduced on 29 October 2024. Irrigation was applied during an eight-hour daily period for 15 min every two hours, resulting in four irrigation events and approximately 60 min of irrigation per day. The plant-house air temperature ranged from 15 to 28°C throughout the experiment. Fish feeding, aeration, water circulation, and the recorded physical and chemical water-quality measurements were monitored throughout the experimental period.

2.3 Chemical analyses of the study sands

Chemical analyses were performed on sand samples collected separately from each basin before and after cultivation. The analyses included pH, EC, alkali-extractable silica, and KCl-extractable mineral nitrogen.

2.3.1 pH measurement

pH is usually measured in saturated soil paste or its aqueous suspension. Before measurement, the instrument is calibrated using two standard buffer solutions, one acidic pH = 4 and the other neutral pH = 7, to ensure measurement accuracy (10). To prepare a 1:1 soil extract, 100 grams of dry soil were air-weighed into a 250 mL conical flask, and 100 mL of distilled water was added. The resulting suspension was then shaken for half an hour and filtered. The pH of the previously prepared extract was measured using a glass electrode. The electrode was washed with distilled water and then inserted into the extract to a depth of approximately 3 cm. The instrument reading was recorded after 30 seconds or until the reading stabilized.

2.3.2 Electrical conductivity measurement

A sand-water suspension was created in a 1:1 ratio and was filtered. The conductivity cell was cleaned with distilled water and placed in the filtrate. The EC was measured directly in $\mu\text{S cm}^{-1}$ using the instrument as mentioned above (Al-Mawsili & Al-Khafaji, 2014). The extraction was carried out with the same ratio for all the samples.

2.3.3 Determination of alkali-extractable silica

Five grams of each sand samples were taken into the balance and also 100 mL of a sodium hydroxide solution of 0.5 N concentration was added to it. The flask with the mixture of sand and the sodium hydroxide solution was set for heating for one hour by connecting it to a reflux condenser. After the end of this step the residue was separated from the solution and the alkali-extractable silica fraction was obtained according to (Jackson, 1965). Since this method represents an operational alkaline extraction, this fraction is called alkali-extractable silica rather than total SiO_2 .

2.3.4 Determination of KCl-extractable mineral nitrogen

Ten grams of air-dried and finely ground sand were placed in a flask, and 100 mL of 2 N KCl solution was added. The suspension was shaken for 30 min and filtered. A 5 mL aliquot of the extract was transferred to the distillation flask of a Micro-Kjeldahl apparatus. Magnesium oxide (0.2 g) and Devarda's alloy (0.2 g) were added to release ammonium and reduce nitrate to ammonium, respectively. The distilled ammonia was collected in 5 mL of boric acid indicator solution and titrated with 0.005 N sulfuric

acid until the endpoint changed to light pink. A reagent blank was prepared using distilled water instead of the sand extract (Hassan et al., 2009). Because no acid digestion of the sand was performed, the result is reported as KCl-extractable mineral nitrogen rather than total soil nitrogen.

2.4 Statistical analysis

Each sand type included three independent basins sampled before and after cultivation ($n = 3$ paired observations). Separate paired-samples t-tests were used to evaluate the before–after change within each sand type because the same basin constituted the experimental unit at both sampling times. Plant species was not included as an analytical factor because the three species were co-cultivated in every basin and the chemical endpoint was one basin-level sand sample at each time point. Mean paired changes, 95% confidence intervals, t statistics with 2 degrees of freedom, and exact p-values are reported; values smaller than 0.001 are presented as $p < 0.001$. Ordinary percentage change was not calculated for pH because pH is logarithmic. Standardized effect sizes were not emphasized because the very small sample size and zero or near-zero variance in several paired differences produced unstable and excessively inflated standardized estimates. For Jalawla mineral nitrogen, the paired differences were identical across the three basins; therefore, the variance of the paired differences was zero and the paired t statistic was not estimable.

3. Results and Discussion

3.1 Changes in pH of Karbala and Jalawla sands

The paired-samples analysis showed a decrease in pH in both sands (Table 1). Karbala sand decreased from 6.360 to 5.293, corresponding to an absolute decrease of 1.067 pH units (95% CI: 1.038–1.096), $t(2) = 160.000$, $p < 0.001$. Jalawla sand decreased from 6.000 to 5.237, corresponding to an absolute decrease of 0.763 pH units (95% CI: 0.618–0.908), $t(2) = 22.564$, $p = 0.002$.

The lower pH values indicate acidification during the cultivation period. Potential mechanisms include nitrification, decomposition of organic matter, root exudation, and the release of hydrogen ions during transformations of ammonium supplied through fish water. Although moderate acidification may increase the availability of some nutrients, excessive or persistent acidification may reduce the availability of others and should not automatically be interpreted as an improvement (Qiu et al., 2024).

Lv et al. (14) reported that nitrogen inputs and intensive irrigation can contribute to decreases in soil pH. During nitrification, ammonium (NH_4^+) is oxidized to nitrate (NO_3^-), releasing hydrogen ions and promoting acidification. Therefore, continued pH monitoring is required when Sandponics systems are operated over longer periods.

Table 1. Mean pH values of Karbala and Jalawla sands before and after cultivation

Soil	Condition	Mean	Std. Deviation	Paired t (df = 2)	p-value	Absolute change (pH units)
Karbala	Before	6.360	0.000	160.000	$p < 0.001$	1.067
Karbala	After	5.293	0.01155			
Jalawla	Before	6.000	0.000	22.564	$p = 0.002$	0.763
Jalawla	After	5.237	0.05859			

3.2 Changes in electrical conductivity of Karbala and Jalawla sands

EC decreased significantly in both sands (Table 2). In Karbala sand, EC decreased from 1623.333 to 319.000 $\mu\text{S cm}^{-1}$, a mean paired decrease of 1304.333 $\mu\text{S cm}^{-1}$ (95% CI: 1193.174–1415.492), $t(2) = 50.487$, $p < 0.001$, equivalent to 80.349%. In Jalawla sand, EC decreased from 1586.333 to 191.640 $\mu\text{S cm}^{-1}$, a mean paired decrease of 1394.693 $\mu\text{S cm}^{-1}$ (95% CI: 1392.034–1397.352), $t(2) = 2256.430$, $p < 0.001$, equivalent to 87.919%.

The very large EC decreases most plausibly indicate extensive leaching of soluble salts and ions through the highly permeable sandy media during repeated irrigation and drainage. The larger decrease in Jalawla sand suggests greater removal of soluble ions under the operating conditions.

Nevertheless, low EC alone does not establish an overall improvement because nutrient ions may also have been lost; EC and nutrient concentrations should therefore be interpreted together (Zhang et al., 2024).

Ahmed et al. (2020) demonstrated that EC is strongly associated with soil chemical composition and management conditions. Differences between that study and the present experiment may reflect the continuous water circulation, drainage, low buffering capacity, and distinct organic-matter conditions of the Sandponics media.

Table 2. Mean electrical conductivity of Karbala and Jalawla sands before and after cultivation

Soil	Condition	Mean ($\mu\text{S cm}^{-1}$)	Std. Deviation	Paired t (df = 2)	p-value	Decrease (%)
Karbala	Before	1623.333	44.74744	50.487	$p < 0.001$	80.349
Karbala	After	319.000	0.00000			
Jalawla	Before	1586.333	1.15470	2256.430	$p < 0.001$	87.919
Jalawla	After	191.640	0.83235			

3.3 Changes in alkali-extractable silica in Karbala and Jalawla sands

Alkali-extractable silica decreased significantly in both sands (Table 3). Karbala sand decreased from 0.9567% to 0.7600%, a mean paired decrease of 0.1967 percentage points (95% CI: 0.1824–0.2110), $t(2) = 59.000$, $p < 0.001$, equivalent to 20.557%. Jalawla sand decreased from 0.9667% to 0.7667%, a mean paired decrease of 0.2000 percentage points (95% CI: 0.1752–0.2248), $t(2) = 34.641$, $p = 0.001$, equivalent to 20.690%.

Because the analytical method used 0.5 N NaOH, these values represent an operationally defined alkali-extractable fraction and not the total silica content of the sands. The decrease may reflect dissolution, leaching, plant uptake, or transformation of poorly crystalline silica phases during cultivation. Acidification and increased biological activity in the root zone may accelerate the release and redistribution of silica (Wang et al., 2025; Brady & Weil, 2017).

Organic acids released by roots and microorganisms can increase dissolution of silicates and transfer of silicon (Welch & Ullman, 1993). In this regard, a decrease noticed cannot be explained as a direct improvement in the quality of sand without measuring silicon dissolved, silicon uptake by plants, and total silica balance.

Table 3. Mean alkali-extractable silica in Karbala and Jalawla sands before and after cultivation

Soil	Condition	Mean alkali-extractable SiO ₂ (%)	Std. Deviation	Paired t (df = 2)	p-value	Decrease (%)
Karbala	Before	0.9567	0.00577	59.000	p < 0.001	20.557
Karbala	After	0.7600	0.00000			
Jalawla	Before	0.9667	0.00577	34.641	p = 0.001	20.690
Jalawla	After	0.7667	0.00577			

3.4 Changes in KCl-extractable mineral nitrogen in Karbala and Jalawla sands

KCl-extractable mineral nitrogen decreased in both sands (Table 4). In Karbala sand, the mean decreased from 16.400 to 14.433 mg kg⁻¹, a mean paired decrease of 1.967 mg kg⁻¹ (95% CI: 1.342–2.592), $t(2) = 13.536$, $p = 0.005$, equivalent to 11.992%. In Jalawla sand, the mean decreased from 18.133 to 17.133 mg kg⁻¹, a numerical decrease of 1.000 mg kg⁻¹ or 5.515%.

For Jalawla sand, the paired difference was exactly 1.000 mg kg⁻¹ in each of the three basins. Consequently, the variance of the paired differences was zero, and a conventional paired t statistic and p-value could not be estimated. This result is therefore reported as a consistent numerical decrease across the three independent basins and is not described as statistically significant.

The decrease in the KCl-extractable mineral nitrogen pool may reflect rapid plant uptake by the three leafy crops, nitrate leaching through the sand, microbial transformations, or a combination of these mechanisms. Intensive vegetable cultivation is particularly susceptible to nitrogen loss during a growing season because crop demand and water movement are high (Hu et al., 2024; Lu et al., 2021). Thus, the decrease should not be interpreted as an improvement unless nutrient inputs, crop uptake, and leaching losses are evaluated together.

Table 4. Mean KCl-extractable mineral nitrogen in Karbala and Jalawla sands before and after cultivation

Soil	Condition	Mean mineral N (mg kg ⁻¹)	Std. Deviation	Paired t (df = 2)	p-value	Decrease (%)
Karbala	Before	16.400	0.45826	13.536	p = 0.005	11.992
Karbala	After	14.433	0.37859			
Jalawla	Before	18.133	0.15275	Not estimable ¹	—	5.515
Jalawla	After	17.133	0.15275			

¹ The paired differences were identical across the three Jalawla basins (1.000 mg kg⁻¹), producing zero variance; therefore, the paired t statistic was not estimable.

3.5 Study limitations

The study did not include an untreated, unplanted, or conventionally irrigated control because its primary purpose was to compare Karbala and Jalawla sands under the same Sandponics conditions. Therefore, temporal changes cannot be attributed exclusively to the Sandponics system. In addition, the three replicate basins for each sand type received water from one common fish tank, so possible tank-level variation could not be separated completely from sand-type variation. The number of samples taken was limited ($n = 3$ for each sand type), and all three species were grown together in the same basin, so it is not

possible to assess whether the effects on the chemistry of the sand were specific to the species used. When drawing general conclusions from this study it is important to keep in mind that there were limitations to this study.

4. Conclusions

In the paper, we compared the two types of sand during a farming experiment. Differences in pH, electrical conductivity, concentrations of extractable silica, and nitric nitrogen were noted. The largest variations were seen in the electrical conductivity of Jalawla sand. In the case of Karbala sand, the largest variations included differences in the pH and nitric nitrogen levels. Changes in electrical conductivity suggest that leaching of salts occurred. Other changes, such as in pH levels, concentrations of nitric nitrogen, and alkali-extracted silica, may have occurred due to leaching, plant uptake, acidification, or mineral transformations. In both sands and samples, conclusions concerning the differences in pH, electrical conductivity, and tensions of silica are based on the fact that the changes reached statistical significance.

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