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Environmental Impacts of Using Municipal Biosolids on Soil, Plant and Groundwater Qualities

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Abstract: This study was conducted to evaluate the effect of three different rates of municipal biosolids produced in Qatar on plant characteristics and soil texture and its potential impacts on groundwater. *Petunia atkinsiana*, was used in this study. The experiment took place in a greenhouse in pots with soil mixed with 0, 3, 5, and 7 kg/m² biosolids. Pelletized class A biosolids from the Doha North Sewage Treatment Plant were used. Results revealed significant differences in all measured parameters, which were affected by biosolid treatments compared to the control treatment. Electrical conductivity, pH, macro and micronutrients and heavy metals were significantly affected by biosolid treatments. The comparison of the discovered levels against the international acceptable ceilings of pollutants indicated the advantages of utilizing class A biosolids, as they were well below the international acceptable levels and showed the best test rates, indicating that the product is a sustainable and efficient organic fertilizer for ornamental plants. Furthermore, the results highlight no potential significant impacts on groundwater due to trace presence of heavy metals, owing to the nature of deep groundwater in Qatar and the usage of modern irrigation devices that fulfil the exact needs of plants in a harsh climate and high evaporation rate.

Keywords: biosolids; agriculture soil; waste management; leachability; groundwater



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1. Introduction

It has become evident that the agricultural movement is struggling to increase productivity to meet food demands from a continuously growing population. Organic fertilizers of different types are essential pillars that ensure agricultural productivity is increased to meet the nutrition needs of the growing population. Biosolids have become a pivotal part of agriculture, which develops every year worldwide [1]. The different application rates of biosolids and their impacts on soil and eventually humans determine whether they are ideal for use as a fertilizer. Qatar does not currently recommend the usage of biosolids in the production of edible plants.

Scientists have been conducting many studies to shed light on the use of biosolids in the production of edible crops, which can be classified as part of humankind's efforts to deal with the human excreta appropriately. Scientists have examined the extended history of landfills as a methodology followed for centuries to deal with using biosolids in crop production. However, many studies have highlighted the catastrophic output of landfills in affecting the arable lands. They spoil land rather than adding value. These problems associated with landfills have increased, requiring a sustainable approach to deal with them and avoid emissions to guarantee environmental conservation [2]. Many studies concluded that treating biosolids might be the most benign methodology to deal with human excreta. Studies have highlighted the role of biosolids in managing the depletion of nutrients by replenishing the soil with the origin of the soil's microbiology, which is activated with the rich content of organic matter they possess. To reinforce this concept,

hundreds of studies have addressed this topic in-depth to illustrate the advantages and disadvantages of using biosolids as an organic fertilizer [3]. Current debates have included strong references to many essential features of such materials, such as high contents of macro- and micronutrients and the texture of such materials, which ensures a slow release of nutrients. These play a vital role in structuring the soil components and increasing the water holding capacity.

Different studies have also been conducted to shed light on the advantages and disadvantages of using biosolids for plant husbandry purposes. [3]. However, none of these studies have fundamentally addressed such advantages and disadvantages in Qatar. This study aims to investigate this topic and provide society with reliable information to decide on whether to use biosolids as an organic fertilizer or not. It is essential to highlight that the term biosolids of class A, refers to a high-quality biosolid specified by the Qatari authorities to be utilized as an organic fertilizer for ornamental plants, describes dewatered sewage products (sludge) that receive a high temperature thermal treatment following U.S. EPA specifications to make it suitable for agricultural use without restrictions as an organic fertilizer for farms and gardens, as defined by EPA's Guide to Part 503 Rule, Chapter 2, Land Application of Biosolids, p. 37.

Researchers such as Singh and Singh [4] have noted that this is a cost-effective and sustainable practice for improving the soil properties, rather than using other harmful agrochemical fertilizers. Although the above advantages might form an irresistible temptation for many communities to use this option, scientists have also discussed the potential adverse impacts of such products, such as heavy metal pollutants levels. Such pollutants can cause many human health problems, not being limited to the environment only. Therefore, it is crucial to check whether the utilization of biosolids in ameliorating soils is a sustainable approach.

Farmers from different parts of the world have been using biosolids as a fertilizer in crop production. It is worth noting that the practice has existed since prehistoric times as farmers in ancient civilizations utilized sludge as an organic fertilizer. Records show that ancient civilizations in Mesopotamia, Egypt, China, and India widely used biosolids as an organic fertilizer in their crop production [1]. The increase in urbanization, population, and the need to meet the increased need for food has led to the increased use of sludge as an organic fertilizer globally [2]. In China, sewage works were expected to produce 46 million tons of sludge for agricultural purposes in 2017. Furthermore, in the same year, sewage was expected to generate 7.7 million tons of organic fertilizer in the U.S. and 2 million tons in Germany [3].

There has been extensive use of sludge products in Europe, where approximately 420 million tons of waste are generated by the residents, and 50 tons are used for energy purposes [4]. The remaining quantity, 370 tons, is used for making inorganic fertilizers. Sludge has been socially accepted in Europe, and there are many communities in Luxembourg, Netherlands, Sweden, and Denmark served by sewage treatment plants. Furthermore, reliable research indicates that about 62% of total sludge quantities in the U.K. are currently recycled to agricultural land [4]. However, laws are restricting its use as a fertilizer. There are also restrictions on the extensive use of sludge as an organic fertilizer in the Middle East, mainly due to social resistance [5]. However, the restrictions could change when this study is completed.

Groundwater is also very crucial as ninety-nine percent of rural areas depend on it [6]. In summary, it is a pivotal natural source in human life that carries specific importance because it acts as a source of life in human and plant life. Qatar is a peninsula that lies in an arid area with a low rainfall average of 75.2 mm/year with high temperatures in summer, and a high evaporation rate. Qatar lacks surface water, and the groundwater is deep in the calcareous limy soil texture. Subsequently, the primary water source is desalinated water obtained from the Gulf [7].

Furthermore, the nature of fractured, carbonated limy soil texture makes the karst aquifers of Qatar susceptible to contamination as pollutants in the case of excessive drainage

can be released rapidly within the karst aquifers moving to cover a more broad area of land [8]. Hence, this study investigates whether biosolids are a potential new source of groundwater pollution as they are newly introduced into the Qatari environment. It is worth noting that Qatari authorities recently specified the usage of biosolids as an organic fertilizer to enrich the barren soil and strictly to fertilize ornamental plants [9].

Therefore, this study aimed to assess the role of biosolids as an organic fertilizer that develops a steady growth of plants and determines the ideal application rate of biosolids produced in Qatar that sustainably enhance soil properties. Furthermore, it aimed to assess whether biosolids are benign for use concerning the levels of pollutants and nutrients in the soil. Such a perspective should investigate the potential adverse impact on Qatar's groundwater in the future.

2. Methodology

2.1. Preparations and Sampling

The materials used included dune sand bought from the approved government source by the Ministry of Municipality and Environment. The soil was mixed well with three different application rates of (3 kg, 5 kg and 7 kg per m²) of class A biosolids, while the fourth treatment was a control treatment of soil only. The biosolid treatments were put in standard square wooden meter boxes with a thickness of 15cm to simulate the actual procedure followed in projects. Pots of a 20 cm size were used and marked with a permanent pen and filled with the specified soil of three replicates, as the experiment was designed to be conducted in a well-controlled environment, before planting unified *Petunia atkinsiana* seedling plants in them as indicative plants with a 15 cm overall height and four leaves for each plant. The pots were placed under shade at the nursery of the Public Parks Department with close daily monitoring from the end of November to March. The recorded growing conditions showed a minimum temperature of 14 °C recorded in January, while the highest temperature was 27 °C recorded in March. Similarly, the degree of shading degree was 50%, while the soil texture was pure dune sand obtained from the approved government source in Qatar prior to mixing it with class A biosolids as specified. The irrigation system flow ranged between one L/pot per day in November up to 2 L/pot per day in March. The flow was controlled by a central irrigation system (a Motorola system, company, city, state abbrev if USA, country) without adding any type of agrochemical fertilizers and as specified in the Qatar construction specifications QCS 2014. The morphological characteristics of the plants at the end of the study were measured by using a standard measurer and digital Verner calipers where the plant height, stem diameter, leaf width and length and number of flowers were measured. The lab analysis for the soil took place after 3 months to ensure melting and homogenization with the soil. The parameters and lab procedure incorporated testing the dry matter of petunia plants [10], the soil pH using a pH meter and electrical conductivity (EC) by using an EC meter. The following were tested: the sodium adsorption ratio (SAR) (soils), exchangeable sodium percentage [11]; nitrates (PPM) by the spectrometry method [12]; chloride content [4]; free carbonates [13]; organic matter percentage [14,15]; and total nitrogen by a digestion method using sulfuric acid, potassium sulfate and copper sulfate, Devarday's alloy and distillation. Nitrogen was absorbed in boric acid solution and titrated with sulfuric acid, available zinc [11] and available phosphate as PO₄-P [14]; the total phosphorus and heavy metals were also tested [16,17]. The samples were prepared, filtered, and digested [18] before checking by optical inductively coupled plasma-optical emission spectrometry (ICP-OES). This approach uses sequential or simultaneous optical systems and axial or radial viewing of the plasma to describe the multi-elemental determinations by ICP-OES. The method also allowed for the detection of the total phosphorus and heavy metals concentration, as well as the analysis of the detected boron (B), potassium (K), manganese (Mn), magnesium (Mg), calcium (Ca) and iron (Fe). In the process used by ICP, soil samples were digested using a microwave digester, filtered and run by ICP-OES [19].

2.2. Chemical Analyses

Meanwhile, different chemical analyses were performed to evaluate the potential impacts of pollutants on groundwater in the future. Based on the expected frequency of application rates, the differences of residuals between the tested application rates on water by investigating the leachates were assessed. Tests were conducted after three months from the starting date. The biosolid pellets were melted and homogenized with the soil for the analysis process. The leachates were gathered carefully from the saucers of the pots in marked plastic bottles with tight lids for analysis. All details such as the temperature during the test, the volume of leachate added during extraction, the volume of the eluate filtrate and other related information such as date, type of test and the followed procedure were recorded [20]. The test parameters and methodology determined the pH value in the leached solutions resulting from the leaching process using a pH meter and a suspension measured with a pH electrode and the appropriate methodology [18]. Furthermore, the analysis also incorporated measuring the electrical conductivity (EC) by using the conductivity meter and via preparing a suspension. EC measurements were taken at 25 °C, and the EC meter was corrected by multiplying it with the appropriate factor using the form. The process continued to measure the sodium adsorption ratio (SAR) and assessed the levels of sodium [20] as well as calcium, magnesium and exchangeable sodium percentage [11]. The analytical process incorporated nitrate as well as the percentage of sulphate content, chloride and organic matter [4]. Subsequently, it measured the free [13] and total nitrogen in the leachates [21]. Additionally, leachates were prepared and digested properly to measure phosphorus and heavy metals using ICP-OES. The results of all replicates were statistically analyzed using a complete randomized design concept.

2.3. Statistical Analysis

Treatments were arranged using the randomized complete block design (RCBD). The effects of biosolid treatments on plant growth characteristics and heavy metal concentrations were examined using analysis of variance. Paired means comparisons were performed using Tukey's test, and the F-test indicated significant effects at the level of $p < 0.05$. Similarly, the general linear model was used in the statistical analysis with the Minitab software (Minitab, Inc., State College, PA, USA).

3. Results and Discussion

3.1. Plants' Characteristics

The plant characteristics results are presented in Table 1. Furthermore, a comparison between morphological parameters is highlighted in Table 1. A close follow-up of vegetative growth and plant development took place earlier to capture sufficient data that critically decrease the plant's response to the nutrients in the soil [22]. The results of plants' height measurements show highly significant differences among treatments at a p -value of 0.00. Biosolid treatment of 5 kg/m² produced the best height, with an average height of 45 cm, while the lowest height was for the control treatment of soil only with a 20 cm height. Similarly, the treatment with 7 kg/m² biosolids developed a height of only 36.6 cm. On the contrary, the gathered data reveal non-significant differences for the stem diameter with a p -value of 0.715. However, thicker stem diameters occurred with biosolid treatment of 5 kg/m² with a mean diameter of 6 cm, and the lowest was the control treatment of soil only with a diameter of 4.54 cm.

Furthermore, treatment with 7 kg/m² biosolid resulted in a 4.64 cm diameter. The differences in leaf number between the various treatments were significant at a p -value of 0.001, where the highest number of leaves was shown for treatment with 5 kg/m² biosolids with 417 leaves. The control treatment recorded the lowest number of leaves (49), and treatment with 7 kg/m² biosolids gave 379 leaves.

Significant differences continue to notably appear for both leaf width and length among various treatments, with a p -value of 0.028 for leaf width and 0.005 for leaf length, respectively. The results of the means gave the treatment with 7 kg/m² biosolids the widest

leaves with 4.23 cm, while the control treatment of soil only recorded the lowest width of 2.3 cm. Meanwhile, the treatment with 5 kg/m² biosolids indicated a mean of 3.74 cm for leaf width. The treatment with 7 kg/m² biosolids also showed the highest leaf length with an average of 6.41 cm. Similarly, the control treatment of soil only proceeded to show the lowest leaf length with 3.7 cm, and a mean of 6.08 cm for leaf length was noticed in the treatment with 5 kg/m² biosolids. Other significant differences were observed concerning the reproductive structure of *Petunia atkinsiana* at a *p*-value of 0.002. The results revealed the highest intensity of flowering for the treatment with 5 kg/m² biosolids, with a mean of 61 flowers, followed by the treatment with 7 kg/m² with a mean of 59 flowers, while the lowest flowering rate was in the control treatment of soil only with an average of 13 flowers. Simultaneously, differences between plants' dry and fresh weight denoted highly significant differences with a 0.001 *p*-value. The comparison of means can highlight these differences clearly as the control treatment of soil only recorded 11.39% as the lowest dry weight percentage, while the treatments with 7 kg/m² and 5 kg/m² biosolids gave 15.37% and 14.87%, respectively.

These results matched those of other studies and the literature, illustrating biosolids' function as rich organic fertilizer with both macro and micronutrients. Being a clear reflection pertaining to the overall development obtained during the whole season, they are also a strong indicator of the efficiency of soil texture as a source of nutrients [23]. In other words, the results clearly illustrate the efficient functionality of biosolids as an organic fertilizer and highlight their role in developing a good biomass over the whole life cycle of petunia plants. However, some parameters showed better indicators in the 5 kg/m² treatments than the 7 kg/m² treatments, which can be explained by the former meeting the nutritional requirements of petunia better than the latter.

Table 1. Averages and standard deviation for plants' characteristics according to different treatments.

Treatments	Plant Height cm		Stem Diameter cm		No. of Leaves		Leaf Width		Leaf Length		No. of Flowers	
Control	20.00	±0.82	4.54	±0.83	49.33	±3.3	2.33	±0.09	3.77	±0.38	12.67	±0.47
3KG Biosolids	39.33	±3.30	5.27	±1.02	235.00	±48.13	3.77	±0.39	6.00	±0.3	34.67	±13.91
5KG Biosolids	45.33	±3.40	6.06	±2.1	416.67	±69.44	3.74	±0.65	6.08	±0.84	61.00	±3.27
7KG Biosolids	36.67	±3.40	4.64	±0.71	378.33	±94.37	4.23	±0.39	6.41	±0.34	59.00	±2.16

3.2. Chemical Analysis of Soil

Specifying the ideal and benign rate of biosolid application in Qatar refers to the dose that improves soil properties and promotes plant growth in a significant manner, along with achieving a high level of safety in terms of pollutants. The results of chemical analyses of the soil treated with three different application rates of class A biosolids (3, 5 and 7 kg/m²), as presented in Table 2, reveal variable levels of significance pertaining to the tests of crucial parameters.

The pH value indicated highly significant differences at a *p*-value of 0.000. The control treatment of soil evidenced alkaline pH with a mean of 8.27. The biosolid treatments showed success in reducing the pH value to an almost neutral level, where the lowest mean of pH was 6.9 for the treatment with 5 kg/m² followed by an average pH 7.0 for the treatment with 7 kg/m², which confirms the producers' claim that their biosolid product is almost neutral (6.3–6.5 as measured). Such levels played a role in minimizing the stress on plants as noted by monitoring their indicative characteristics.

Table 2. Averages and standard deviation for chemical parameters of different treatments in soil.

Treatments		pH	Plant Testing/ Dry Matter %	Potassium (K) (mg/Kg)	Total Salt as EC(mS/cm)	Sodium Adsorption Ratio	Organic Matter (%)	Free Carbonates (%)	Total Nitrogen (mg/kg)	Chloride Content (%)	Sulphates (%)	Nitrates (mg/Kg)	Total Phosphorus (P) (mg/Kg)	Calcium (Ca) (mg/Kg)	Magnesium (Mg) (mg/Kg)
3 kg/m ² biosolids	±SD	0.1	0.91	40.58	0.07	0.06	0.62	1.35	0.24	0.00	0.00	6.80	0.17	17.69	0.12
	Mean	7.20	13.62	794.64	0.17	0.52	2.72	1.88	2.17	0.02	0.03	22.67	1.43	75.79	4.99
5 Kg/m ² biosolids	±SD	0.05	0.83	24.38	0.04	0.03	0.40	0.39	0.00	0.00	0.01	15.08	0.18	2.22	0.20
	Mean	6.97	14.87	844.55	0.28	0.44	3.50	1.04	2.00	0.02	0.04	29.33	1.50	68.69	5.20
7 kg/m ² biosolids	±SD	0.15	1.71	76.91	0.19	0.11	0.59	0.67	0.82	0.00	0.01	16.97	0.10	7.43	0.52
	Mean	7.00	15.37	788.21	0.36	0.62	3.80	1.04	2.00	0.02	0.04	36.00	1.85	61.26	4.82
Control soil only	±SD	0.09	0.16	56.22	0.004	0.05	0.07	0.27	0.92	0.00	0.01	0.00	0.15	7.10	0.33
	Mean	8.27	11.39	717.60	0.07	0.63	0.76	0.88	2.43	0.02	0.04	24.00	1.28	74.03	4.31

Similar to the pH value, the ratio of organic matter also showed significant differences among the treatments at a p -value of 0.001. Biosolid treatments maintained superiority as compared to the control treatment, with the highest average of 3.80% for the treatments with 7 kg/m², followed by the treatments with 5 kg/m² with a mean of 3.50%, while for the control treatment an average of 0.76% was recorded. This logical sequence proves the biosolid richness in organic matter [1]. Additionally, the test was a revelation for one of the main problems for arable lands nowadays, which is the salinity [24]. The salinity checkup reflected non-significant differences among treatments with a p -value of 0.095.

Electrical conductivity (EC) revealed non-significant differences at a p -value of 0.095. Furthermore, the control treatment of soil only recorded the lowest salinity with 0.07 mS/cm, followed by the treatment with 5 kg/m² biosolids with a mean of 0.28 mS/cm, and the treatment with 7 kg/m² biosolids with a mean of 0.36 mS/cm. Considering that the soil only treatment was taken from the same batch that formed the main components in all treatments, the results can easily be interpreted by attributing this sequence directly to the salts of the added biosolids. A major point in this discussion is that the highest recorded salinity for the treatment with 7 kg/m² is still below the minimum acceptable level of salinity as specified in Qatar [9]. Subsequently, the sodium adsorption ratio (SAR) results indicate non-significant differences among the different treatments, with a p -value of 0.071. The obtained results indicate that the presence of biosolids mitigated this ratio as can be observed by checking the average figures of each treatment, where the control treatment of soil only indicated the highest SAR value with a mean of 0.63, while the treatments of biosolids produced, respectively, 0.62 for 7 kg/m², 0.52 for 3 kg/m² and 0.44 for 5 kg/m² biosolid treatment. These non-significant differences and moderated figures obtained for this parameter show that the suggested application rates do not negatively affect this essential ratio and that they help to enhance the soil's properties.

The results of free carbonate analysis indicated non-significant differences among treatments at a p -value of 0.602. Although this result is expected due to the calcareous type of soils in Qatar, further discussion is recommended to shed light on this important parameter. The control treatment of soil only recorded a mean of 0.88%, while the biosolid treatments indicated means of 1.04% for both treatments of 5 and 7 kg/m² biosolids. Similarly, the mean of 3 kg/m² biosolids treatment showed the highest level with 1.88%. An important point of these outputs is that the biosolid additives did not significantly increase the percentage of free carbonates in the soil, which might have a bad impact on plants due to alkalinity stress, despite the fact that limestone is commonly used during the thickening and dewatering process of biosolids. Similarly, the results of nitrogen, as a core element in plant growth, present in the soil in different forms [20], revealed non-significant differences among treatments at a p -value of 0.43. Subsequently, the means of each treatment highlighted that the control treatment of soil recorded a higher total nitrogen value than the biosolid treatments, with 2.43 mg/kg against 2.0 mg/kg for both treatments with 5 kg/m² and 7 kg/m² biosolids, while the treatment with 3 kg/m² biosolids indicated a total nitrogen ratio of 2.17 mg/kg. The interpretation of these results needs to be considered for the assessment of the indicative plant characteristics to be explainable. The plants' vegetative growth, biomass, stems and flowers were much better in biosolid treatments than in the control treatments of soil only as confirmed by either monitoring or by the results of the statistical analysis, which can be firmly attributed to the level of nutrients supplied by the biosolids and the presence of nitrogen. Hence, it can be concluded that a high percentage of nitrogen was initially utilized to develop growth, which is not the same case in the control treatment as the plants adapted to the low level of nitrogen and other nutrients to regulate their growth accordingly. On the other hand, biosolids are well known for their capability of activating soil microorganisms. They work actively on the organic compounds to make them ready and an essential part of these microorganisms, such as the denitrifying bacteria, which represent 10–15% of soil bacteria, and actively work on soil nitrate to release free nitrogen gas [25]. The lack of organic materials required by these bacteria in the control treatment was one reason for

the insignificant differences among treatments with a slightly higher level of nitrogen in the control treatment than the biosolids treatment. By contrast, this type of bacteria was actively functioning. Similarly, the tangible differences in growth among the treatments should not be overlooked, as one of the primary reasons behind this is the total content of nitrogen in biosolids. Moreover, the interpretation of nitrate results within this experiment highlighted additional points about these results by indicating non-significant differences for nitrate levels versus control treatments at a p -value of 0.678. Furthermore, the highest mean of nitrate levels was discovered in the treatment with 7 kg/m² biosolids with an average amount of 36 mg/kg, followed by treatment with 5 kg/m² biosolids with a mean of 29.33 mg/kg, and the control treatment of soil only with an average of 24 mg/kg; the lowest presence was recorded in the treatment with 3 kg/m² with a mean value of 22.67 mg/kg. The nitrate receives specific consideration as an inorganic type of nitrogen, which is converted by bacterial action into an organic form in the nitrification process and is capable of utilization by plants for growth and production [26]. It is interesting that both groups of soil bacterial microorganisms work on the organic material of fertilizers, which in this study are the class A biosolids. However, such observations can be attributed to many points such as the utilization of nitrogen by plants, the addition of the high level of microorganisms' functionality in the texture of biosolids treatment and the variable levels of the nitrification and denitrification processes, which resulted in the currently acceptable level that was successful in developing petunia plants in season.

The chloride content levels are another important parameter, that showed non-significant differences among treatment at a p -value of 0.2. Moreover, the present levels were low in all treatments, which were revealed to be only 0.02%. This is expected as Doha North Sewage Treatment Plant (DNSTP) gathers its sludge from non-industrial and non-medical areas [27]. Hence, the effects of the usage of water softener containing sodium chloride (NaCl) from domestic effluents will not be considered [28]. Similarly, tests for sulphate, which check for the percentage of sulfate salts [29], showed an average presence of 0.04% in all biosolid treatments as they go through a solid and stable preparation process, while the mean for the control treatment of soil only was 0.03%. Subsequently, the results revealed non-significant differences between treatments in this parameter at a p -value of 0.757.

Phosphorus (P) is another crucial macronutrient after nitrogen [26]. Higher levels of phosphorus turn it into a pollutant that needs to be managed [30]. The results reflected non-significant differences versus treatment with a p -value of 0.487. Additionally, the mean figures of P presence show that the highest presence was discovered in 7 kg/m² biosolids treatment with 1.85 mg/kg, followed by treatment with 5 kg/m² biosolids with an average of 1.50 mg/kg, while the lowest presence of phosphorus was observed in the control treatment with a mean of 1.28 mg/kg. The sequence matches the expectation that the biosolids' phosphorus content is not a discussable issue and was confirmed by many studies [1].

Calcium and magnesium are essential secondary nutrients in the soil. The results of the presence of both calcium and magnesium have pointed out non-significant differences among treatments with a p -value of 0.526 and 0.118, respectively. Calcium's highest presence was observed in treatment with 3 kg/m² biosolids, with an average of 75.79 mg/kg. Similarly, the control treatment of soil only followed due to the high calcium content in the calcareous type of soil [31], with an average of 74.03 mg/kg. The treatments with 5 kg/m² and 7 kg/m² biosolids revealed an average of 68.69 mg/kg and 61.26 mg/kg, respectively. Similarly, the highest level of magnesium was observed in the treatment with 5 kg/m² biosolids, with a mean of 5.20 mg/kg, while the 7 kg/m² treatment recorded a mean of 4.82 mg/kg; the control treatment had an average of 4.31 mg/kg.

Potassium is also a crucial macronutrient required by plants. The results show non-significant differences between treatments at a p -value of 0.203. All the biosolid treatments of different rates recorded a higher potassium presence than the control treatment, whereas the highest level was recorded for treatments with 5 kg/m² with 844.55 mg/kg. Sub-

sequently, the treatment with 7 kg/m² gave 788.21 mg/kg, while the control treatment showed 717.6 mg/kg. Although the results show non-significant differences, the impacts of the dewatering and thickening processes during sludge treatment to produce biosolids have promoted the presence of potassium in biosolid treatments. This is because this process incorporates limestone with potassium to obtain fruitful results. On the contrary, the level of potassium in the control treatment can be attributed to the high level of potassium in Qatari soil [32].

3.3. Heavy Metals (Bo, Zn, Mn, Fe, Al, As, Cd, Co, Cr, Ni, Pb, Sn, Hg)

Biosolid applications for agricultural purposes as an organic fertilizer have become a widespread practice. However, based on biosolids' chemical and physical characteristics, this international concept might face some problems, especially regarding heavy metals. The tested elements were based on the specified parameters to be checked by the government authorities in Qatar as they are known as a potential problem in Qatari soil. Similarly, the same parameters were suggested in the regional GCC countries, which have similar conditions (QCS).

The results of the heavy metals test are highlighted in Table 3. This reveals that mercury (Hg) was below the detection limit of the equipment used. At the same time, the presence of cadmium (Cd) reflected non-significant differences between treatments at a *p*-value of 0.320. It is worth mentioning that cadmium was below the detectable limit in most replicates, which is <0.3 mg/kg, but it should be pointed out that the detected trace levels were found only in biosolid treatments, while it was undetectable in the control treatment. However, these levels are below the minimum international levels accepted in biosolids as is highlighted by a comparison of Tables 4–6. Furthermore, a similar situation appeared with the results of boron (B), which was below the detectable level of <3 mg/kg for all treatments. Only a trace level was discovered in one of the control treatments of soil replicates. This was illustrated statistically, whereas the results indicated non-significant differences between treatments with a recorded *p*-value of 0.441. This minor detected concentration in one replicate can only be attributed to an error in analyzing it. Subsequently, non-significant differences between the treatments and amounts below the detected level means that the levels of this element as a potential pollutant that can be neglected. The same can be said for aluminum (Al) with non-significant differences and *p*-values of 0.254. These results were extended to other heavy metal elements, especially since non-significant differences between treatments continue to be observed for cobalt (Co) at a *p*-value of 0.545, chromium (Cr) with 0.568, nickel (Ni) with 0.07, lead (Pb) with 0.180, arsenic (As) with 0.379 and tin (Sn) with 0.180. The results of these heavy metals were considered promising indications concerning the usage of biosolids as an organic fertilizer [31]. Simultaneously, copper (Cu) and iron (Fe) revealed significant differences between treatments as the *p*-value and statistical analysis were recorded as 0.001 for copper and 0.00 for the iron. Nevertheless, the level of copper was very negligible, as highlighted via comparison against the international levels (Tables 4–7).

Other essential elements such as manganese (Mn) and zinc (Zn) were investigated. The statistical results did not reflect significant differences versus the treatment for manganese at a *p*-value of 0.118. However, the highest was found in the treatment with 7 kg/m² biosolids with a mean concentration of 103.53 mg/kg. Simultaneously, the treatment with 5 kg/m² showed an average of 91.35 mg/kg, and finally the control treatment had an average manganese content of 89.61 mg/kg. The level in the control treatment can be firmly attributed to the actual content of manganese in the soil. In contrast, the trace presence in the biosolid treatments, which was slightly higher than in the control treatment, was caused by biosolids' soil additives at different rates. Unlike manganese, the presence of zinc indicated significant differences versus control treatments at a *p*-value of 0.025 as per the results. Furthermore, by checking the average presence of zinc in each treatment, it was discovered that the control treatment of soil without additives reflected only 36.6 mg/kg, which is low compared to the biosolid treatments, which show 88.42

mg/kg for the 7 kg/m² treatment and 80.74 mg/kg for the 5 kg/m² treatment. It is clear that the contents of heavy metals in biosolids are higher, including zinc, as pointed out by many studies [1]. Similarly, the comparison with the international ceilings of heavy metals in soil should highlight the situation and indicate whether there is a problem with these levels or not.

Table 3. Averages and standard deviation for heavy metals according to different treatments in soil.

Treatments		Zinc (Zn) (mg/Kg)	Iron (Fe) (mg/Kg)	Aluminum (Al) (mg/Kg)	Arsenic (As) (mg/Kg)	Cadmium (Cd) (mg/Kg)	Cobalt (Co) (mg/Kg)	Chromium (Cr) (mg/Kg)	Nickel (Ni) (mg/Kg)	Lead (Pb) (mg/Kg)	Tin (Sn) (mg/Kg)
3 kg/m ² biosolids	±SD	4.68	0.36	0.21	0.39	0.01	1.13	2.40	0.36	0.42	0.31
	Mean	72.71	3.03	4.16	2.02	0.31	3.01	11.38	14.31	2.63	1.40
5 Kg/m ² biosolids	±SD	6.22	0.06	0.35	0.57	0.01	1.29	1.65	1.48	0.36	0.48
	Mean	80.74	2.61	4.03	2.44	0.31	3.77	12.94	15.47	2.79	1.76
7 kg/m ² biosolids	±SD	19.80	1.53	0.48	0.79	0.23	0.86	2.06	0.47	0.89	0.53
	Mean	88.42	3.65	3.84	1.55	0.50	2.84	14.24	14.12	3.39	2.08
Control soil only	±SD	18.00	0.12	0.27	0.44	N.D	0.53	4.50	1.51	0.41	N.D
	Mean	36.60	1.77	3.45	1.52	N.D.	2.28	10.33	12.06	1.98	N.D

3.4. Comparison against International and Regional Standards

The comparison with the acceptable international limits will shed a clear light on Qatar's level of treatment, biosolid functionality and the impact on the soil according to the different experimented rates. These different standards are all measured in mg/kg. This comparison is essential to develop a confident assessment. In contrast, the interpretation of the results of these rates in soil should be integrated with other outputs such as the results of the plants' characteristics. These should be analyzed holistically before recommending the proper application rate, which can significantly promote plant growth and enhance the soil properties without any harmful impact on the soil's chemical and physical characteristics. Moreover, it can be seen that the figures recorded for the different biosolid parameters produced in Qatar are the most benign in the world, which means that pollutants and other toxic heavy metals will not affect the concept of using biosolids as an organic fertilizer. On the other hand, such sustainable practice will increase soil fertility without significant detrimental impacts on Qatari soil. Consequently, the evaluation of these rates will not be considered without investigating these parameters' impacts on the groundwater to finalize it.

Table 4. Comparison between the levels of heavy metals in soil fertilized with three different rates of biosolids and the international acceptable standards.

Heavy Metal Limit Values in Sludge		Zn	Cu	Ni	Cd	Pb	Hg	Cr	As	Co
Europe										
Directive 86/278/EEC		2500–4000	1000–1750	300–400	20–40	750–1200	16–25	-		
Austria	Lower Austria	1500	300	25	2	100	2	50		10
	Upper Austria	2000	500	100	10	400	10	500		
	Burgenland	2000	500	100	10	500	10	500		
	Voralberg	1800	500	100	4	150	4	300		
	Steiermark	2000	500	100	10	500	10	500	20	100
	Carinthia	1800	300	80	2.5	150	2.5	100		
Belgium	Flanders	900	375	100	6	300	5	250	150	
	Walloon	2000	600	100	10	500	10	500		
Bulgaria		3000	1600	350	30	800	16	500		
Cyprus		2500–4000	1000–1750	300–400	20–40	750–1200	16–25	-		
Czech Republic		2500	500	100	5	200	4	200	30	
Denmark		4000	1000	30	0.8	120	0.8	100	25	
Estonia		2500	1000	300	20	750	16	1000		
Finland		1500	600	100	3	150	2	300		
France		3000	1000	200	20	800	10	1000		
Germany		2500	800	200	10	900	8	900		
Germany	<5% P ₂ O ₅	1500	700	80	2.5	120	1.6	100		
	>5% P ₂ O ₅	1800	850	100	3	150	2	120		
Greece		2500–4000	1000–1750	300–400	20–40	750–1200	16–25	500		
Hungary		2500	1000	200	10	750	10	1000/1	75	50
Ireland		2500	1000	300	20	750	16	-		
Italy		2500	1000	300	20	750	10	-		
Kosovo		2500–4000	1000–1750	300–400	20–40	750–1200	16–25	100–500		
Latvia		2500	800	200	10	500	10	600		
Lithuania	Class 1	300	75	50	1.5	140	1	140		
	Class 2	2500	1000	300	20	750	8	400		
Luxembourg		2500–4000	1000–1750	300–400	20–40	750–1200	16–25	1000–1750		
Malta		2000	800	200	5	500	5	800		
Montenegro	Class A	600	300	60	5	120	5	100		
	Class B	1200	600	100	10	200	10	250		
	Class C	2400	1000	300	20	750	16	1000		
Netherlands		300	75	30	1.25	100	0.75	75	15	
Norway		800	650	50	2	80	3	100		
Poland		2500	500	300	20	750	16	1000		
Portugal		2500	1000	300	20	750	16	1000		
Romania		2000	500	100	10	300	5	500	10	50
Slovakia		2500	1000	300	10	750	10	1000		
Slovenia		100	30	30	0.5	40	0.2	40	20	
Spain		2500	1000	300	20	750	16	1000		
Spain		4000	1750	400	40	1200	25	1750		
Sweden		800	600	50	2	100	2.5	100		
Switzerland		2000	600	80	5	500	5	500		
United Kingdom						1200				
3 kg/m ² biosolid average values		72.71	52.60	14.31	0.31	2.63	>0.01	11.38	2.02	3.01
5 kg/m ² biosolid average values		80.74	57.40	15.47	0.31	2.79	>0.01	12.94	2.44	3.77
7 kg/m ² biosolid average values		88.42	63.70	14.12	0.50	3.39	>0.01	14.24	1.55	2.84

Refs. [33–37].

Table 5. Comparison between levels of heavy metals in soil fertilized with three different rates of biosolids and the local and regional acceptable standards.

Middle East		Zn	Cu	Ni	Cd	Pb	Hg	Cr	As	Se	Co
GCC		500	400	200	20	300	10	300	10	50	
UAE		200	100	200	20	200	10	200	20	50	
Abu Dhabi	Unrestricted	300	150	60	1	300	1	400	20	3	
	Controlled	2500	1000	300	20	750	10	1000	75	50	
Dubai		3000	1000	300	20	1000	10	1000		50	
Oman		3000	1000	300	20	1000	10	1000		50	
Saudi Arabia		7500	4300	420	85	840	57	3000	75	100	
Qatar		2500	1000	200	20	300	10	300	10	50	
Bahrain											
Kuwait											
Egypt		2800	1500	420	39	300	17	1200	41	36	
Jordan (1)	Class 1	2800	1500	300	40	300	17	900	41	100	
	Class 2	4000	3000	400	40	840	57	900	75	100	
	Class 3	7500	4300	420	85	840	57	3000	75	100	
Syria (2)	Class A	200	100	60	3	150	1	100	20	5	
	Class B	700	375	125	5	150	4	250	20	8	
	Class C	2500	1500	270	20	300	15	500	20	50	
	Class D	2800	1500	300	32	400	19	600	30	90	
Palestine	As Jordan										
Tunisia		2000	1000	200	20	800	10	500			
Turkey		2500	1000	300	10	750	10	1000			
3 kg/m ² biosolid average values	Class A	72.71	52.60	14.31	0.31	2.63	>0.01	11.38	2.02		3.01
5 kg/m ² biosolid average values	Class A	80.74	57.40	15.47	0.31	2.79	>0.01	12.94	2.44		3.77
7 kg/m ² biosolid average values	Class A	88.42	63.70	14.12	0.50	3.39	>0.01	14.24	1.55		2.84

(1). Class 1—agriculture, Class 2—soil improvement, Class 3—landfill. (2). A—gardens, B—public access areas, C—green areas, D—agriculture. 3. References: [37–46].

Table 6. Comparison between levels of heavy metals in soil fertilized with three different rates of biosolids and other international acceptable standards.

International Standards	Type	Zn	Cu	Ni	Cd	Pb	Cr	Hg	As	Co
EC	(1)	2500–4000	1000–1750	300–400	20–40	750–1200		16–25		
US EPA(2)	Exceptional quality	2800.00	1500.00	420.00	39.00	300.00	1200.00	17.00	41.00	
	Ceiling concentration	7500.00	4300.00	420.00	85.00	840.00	3000.00	57.00	75.00	
Canada (3)	Class A	500–700	100–400	62.00	3.00	150.00	100–210	0.8–2	13.00	34.00
	Class B	1850–4200	760–2200	180–420	10–34	500–1100	1060–2800	4–15	41–170	150.00
Australia (4)	Grade C1	200–250	100–200	60.00	1.00	150–300	100–400	1.00	20.00	
	Grade C2	2500.00	2500.00	270.00	20.00	420.00	500–3000	15.00	60.00	
New Zealand	Grade A	300.00	100.00	60.00	1.00	300.00	600.00	1.00	20.00	
	Grade B	1500.00	1250.00	135.00	10.00	300.00	1500.00	7.50	30.00	
South Africa	Class A	2800.00	1500.00	420.00	40.00	300.00	1200.00	15.00	40.00	
	Class B	7500.00	4300.00	420.00	85.00	840.00	3000.00	55.00	75.00	
Brazil		2800.00	1500.00		39.00	300.00	1000.00	17.00	41.00	
Mexico		2800.00	1500.00	420.00	39.00	300.00	1200.00	17.00	41.00	
China	Soil pH < 6.5	2000.00	800.00	100.00	5.00	300.00	600.00	5.00	75.00	
	Soil pH > 6.5	3000.00	1500.00	200.00	20.00	1000.00	1000.00	15.00	75.00	
3 kg/m ² biosolid average values	Class A	72.71	52.60	14.31	0.31	2.63	11.38	>0.01	2.02	3.01
5 kg/m ² biosolid average values	Class A	80.74	57.40	15.47	0.31	2.79	12.94	>0.01	2.44	3.77
7 kg/m ² biosolid average values	Class A	88.42	63.70	14.12	0.50	3.39	14.24	>0.01	1.55	2.84

(1) For each country, the first row of values applies to unrestricted use; the second row of values applies to restricted use in agriculture. Some countries/states have additional grades for other sludge use purposes. For unrestricted use, sludge must also comply with stabilization and/or microbiological standards. (2) Unrestricted and restricted use, respectively. (3) Individual states may set their values indicated by ranges. (4) Guideline values if there are no state regulations. Ranges indicate the different values adopted by states. (5) Ref. [47].

3.5. Chemical Analysis of Major Elements in Soil Leachates

Chemical analysis of leachates was conducted, and the statistical analysis revealed that there were effects of statistically variable differences among various treatments. The results are highlighted in Table 8. Non-significant differences were verified in pH value among treatments at a p -value of 0.231. The observation of means shows that higher pH of 8.33 was recorded in control treatment of soil only, while slightly lower values were noticed in biosolid treatments, for instance, 5 and 7 kg/m² had pH values of 8.13 and 8.23, respectively. Although the class A biosolids of in Qatar are almost neutral [48], this neutrality cannot affect the nature of alkaline soil in Qatar. However, it can be considered to be at the edge of neutrality.

Similarly, electrical conductivity measurements and analysis indicated non-significant differences among treatments at a p -value of 0.6. The sequence of means highlights that higher salinity was found in the control treatment of soil only with 3.12 ms/cm, while the lowest was in the 5 kg/m² treatment with 2.72 ms/cm, along with 3.09 ms/cm for the treatment with 7 kg/m² biosolids. Such moderated levels did not affect the growth development of the petunia plants as highlighted by the plants' characteristics. Moreover, it should be recognized that organic matters in biosolids preserve salts and water as they increase the water holding capacity of soil [18], which can create such slight differences in leachates.

Unlike the above parameters, the results reflected significant differences in total nitrogen at a p -value of 0.009. The highest level of total nitrogen was in the treatment with 7 kg/m² biosolid with a total of 37.12 mg/L, followed by the treatment with 5 kg/m² with a total of 22.21 mg/L, while the control treatment of soil only had the lowest nitrogen content with 6.07 mg/L.

The total nitrogen is expected to show the presence of nitrogen of different forms in the soil, reflected in the leachates, as biosolids are known for high levels of nitrogen [1]. Furthermore, these results were affirmed by the vigorous growth of petunia plants in biosolid treatments compared to the control treatment of soil only. Despite these significant differences in total nitrogen, the results of a major form of this mineral (nitrate) revealed non-significant differences at a p -value of 0.119, with the highest presence observed in treatments with 7 and 5 kg/m² biosolids with averages of 26.33 and 16.0 mg/L, respectively, while the control treatment showed a level of 4.33 mg/L. Nitrate can be described as a two-sided sword as it is also essential for plants' nutrition. However, its solubility makes it an indicator of groundwater contamination, as shown by many studies and many nutrition manuals. These non-significant differences point out the role of organic material in minimizing the leaching of nutrition and keeping it available for plants within the root zone. Simultaneously, this allows the plants to utilize a good amount of nitrate in the growing process as reflected in the biological parameters of petunia and the large difference in vegetative growth between the biosolid treatments and the control treatment of soil only. Furthermore, the pelletized industrial form of class A biosolids should not be overlooked as this was designed to simplify the mixing process and to ensure a slow release of nutrients over the whole growing season. Such a prominent feature, which the producers designed for the said purposes, will also unintentionally minimize the harmful impact of nitrate on groundwater and convey a promising message to environmentalists.

The chloride contents indicated significant differences at a p -value of 0.005, with the highest percent for the 7 kg/m² biosolids treatment having 0.005%, followed by the other treatments with 5 and 3 kg/m² biosolid having 0.002%, while the control treatment of soil only possessed a chloride content of 0.001%. Such significant differences can be attributed to the nature of biosolids rich in different components that contain many nutrients that form several compounds with chloride to increase its presence in soil and soil leachates.

Contrary to the chloride percentage results, the sulfates percentage revealed non-significant differences at a p -value of 0.473. The average presence of sulfates was the highest in the control treatment with a level of 0.3 as compared to the treatments with 5 and 7 kg/m² biosolids which had levels of 0.03. The sulfates in soil colloids are known for

their variable presence in different forms as organic and inorganic or soluble and insoluble. However, it should be noted that sulfates are not considered a problem in Qatar or any other alkaline types of soil contrary to acidic soils, especially in rainy areas [26].

Other significant differences were shown by the results for the second nourishment element for plants, which is phosphorus with a p -value of 0.001. The average presence of phosphorus in the leachates of each treatment illustrated apparent differences between biosolid treatments and the control treatment, as the treatments with 5 and 7 kg/m² biosolids reflected values of 2.60 and 2.12 mg/L, respectively, as compared to 0.21 mg/L in the control treatment of soil only. This result is commensurate with the outputs of many studies that looked at municipal biosolid and sewage sludge, which were in agreement concerning the fatty contents of biosolids with phosphorus [1]. However, it is important to consider that the depth of aquifers in Qatar in calcareous soil and a reasonable rate of biosolids application along with a prohibition on using landfills will avoid contamination problems with phosphorus, especially since it is mandated for all landscaping projects in Qatar to use efficient irrigation systems. Furthermore, the irrigation systems in Qatar supply plants with adequate irrigation to meet their needs and minimize the excessive leaching of nutrients; in addition, the hot climate and high evaporation rate prevent water from going deep towards the groundwater.

The variability was not restricted to the above parameters as the results highlighted non-significant differences for the third important element for plants, which is potassium, at a p -value of 0.11. This result meets the expectations of a loamy and alkaline soil in Qatar, where potassium is an abundant element and highly available. The highest potassium level was confirmed in the 7 kg/m² biosolids treatment at 10.46 mg/L, followed by the 5 kg/m² biosolids treatment at 6.10 mg/L, while the control treatment of soil only showed the lowest concentration of potassium in leachates at 4.61 mg/L. The slightly higher level of potassium in the biosolid treatments can be explained due to the industrialization process with lime during the dewatering stage in addition to potassium abundance in alkaline soil such as that in Qatar. Furthermore, being a soluble element, potassium needs excessive water and acts as a solvent thereby becoming a threat for groundwater; this is not possible with modern irrigation devices, and the current daily applied amount is accuracy in accordance with the actual plants' needs. Subsequently, the calcium and magnesium levels in leachates showed contradictory results, as the statistical analysis pointed out non-significant differences for calcium at a p -value of 0.11 and significant differences for magnesium at a p -value of 0.037. The presence of calcium in leachates, calculated by mg/L, was recorded as the highest in the treatment with 3 kg/m² of biosolids at 421.53, followed by the control treatment of soil, at only 380.62 mg/L, and the lowest level was in the treatment with 5 kg/m², with a level of 287.57 mg/L. Within the same context, biosolid treatments reflected a higher presence of magnesium, while the lowest level was in the control treatment with 21.51 mg/L. The biosolid treatments show functional ascendancy, starting from 42.43 mg/L for the 3 kg/m² treatment and ending with the highest presence of Mg in the 7 kg/m² treatment with a level of 66.49 mg/L. It is crucial to reconfirm that the fluctuation in levels did not affect the growth or the balanced texture of biosolids rich with many competing minerals that play a role in this variation. Similarly, the results illustrate that the level of calcium was much higher in general than magnesium and that the calcium abundance was dominant with a variable response to the soil additives. However, magnesium responded positively to the levels of biosolid additives with significant statistical differences.

Unlike the above major elements, sodium is not highly needed by plants, although it participates in chlorophyll synthesis to a certain extent [12]. Furthermore, its high solubility in water might be a problem affecting groundwater quality [5]. The statistical analysis of sodium in soil leachates indicates significant differences at a p -value of 0.008. Similarly, the average presence of sodium was recorded at higher levels in the control treatment of soil only with 16.49 mg/L, while the lowest level was found in treatment with 5 kg/m² biosolid with 1.18 mg/L, and the 7 kg/m² treatment had 1.71 mg/L. The results can be interpreted by highlighting that the lack of obstruction of the leachability of minerals in the

control treatment (such as by organic matters) leads to a higher level of leached sodium, unlike the situation with the soils fertilized with a rich organic fertilizer such as biosolids, which act as a barrier against excessive mineral leaching, including sodium [49].

3.6. Chemical Analysis of Heavy Metals in Soil Leachates

As biosolids are a newly introduced product in the Qatari environment and are rich in nutrients and different types of heavy metals, it is important to investigate and assess the potential impacts of such materials on the environment and also on the groundwater more specifically. This study was designed to satisfy this need via the detailed chemical analysis of soil leachates fertilized with biosolids at different application rates. Furthermore, the study aimed to evaluate the most suitable and non-harmful rate to be recommended for use in Qatar. Based on the discovered leaching behavior, which is discussed below, the analysis of heavy metals can be categorized into three groups: group 1, which revealed positive leachability where the presence of these parameters in the leachates of biosolid treatments were higher than the same parameters in the control treatment leachate; group 2, which indicated a lower presence in the leachates of the biosolid treatments comparing to the same parameters in leachates of the control treatment; and group 3, which showed non-detective concentrations in the leachates or they were below the detection limits.

3.6.1. Group 1

Statistical analysis of soil leachates revealed significant differences versus treatments for boron (B) at a p -value of 0.01. The highest presence of boron was discovered in treatment with 7 kg/m² biosolids with an average of 1.01 mg/L, followed by the treatment with 5 kg/m² biosolids with 0.98 mg/L, and lastly the control treatment of soil only with 0.62 mg/L. This sequence of results is logical as biosolids are known as a rich source of heavy metals in general, including boron [1]. However, monitoring the growth of *Petunia* plants did not reflect any signs or symptoms of boron deficiency during the study period. The results for copper, as per the statistical analysis, reflected high significant differences among treatments showing a p -value of 0.00. Furthermore, the lowest level was for the control treatment with 0.02 mg/L, which is understood as due to the lack of biosolids and its discharged residues. Unlike the control treatment, the treatments with biosolids of different rates indicated an increase starting from 11.02 mg/L for the treatment with 3 kg/m², then 13.36 mg/L for the treatment with 5 kg/m², reaching the peak with the treatment with 7 kg/m² biosolids with an average level of 15.8 mg/L. The differences are clear between treatments as the level of copper positively increased with the application rate, which can be attributed to the copper content of biosolids, as discussed by many studies. However, comparison against the international levels confirmed that these detected levels are trace and can be neglected.

3.6.2. Group 2

Zinc is another heavy metal that interacts with many biological activities of plants and is required in trace levels [50]. The results show non-significant differences versus treatments for the zinc presence at a p -value of 0.123. Similarly, the average levels of zinc in the treatments indicated that the biosolid treatments minimized the presence of zinc in soil leachates, which is also pointed out by many studies due to the high amount of organic matter contained in biosolids [51]. Although zinc is an insoluble metal in water, its reaction with other components can create compounds, which possess solubility and can threaten groundwater when leached by water [52]. Considering the above will help in interpreting the results of the discovered zinc presence in soil leachates as the highest level was recorded in the control treatment of soil only with an average of 0.009 mg/L; there is no organic matter to hold it, despite the daily leaching process for zinc compounds with irrigation water. For the biosolids treatments, the results revealed that the 5 kg/m² treatment came second after the control treatment with an average level of 0.006 mg/L. Simultaneously, both treatments with 3 and 7 kg/m² of biosolids recorded a similar average

level of 0.003 mg/L. These differences between biosolid treatments can be attributed to the variable release of nutrients from the pelletized biosolids due to the nature of the formula, which was designed to ensure a slow release of nutrients in a process controlled by many variable factors such as the activities of the microorganisms in soil. Similarly, organic matter plays a vital role in minimizing the leachability of nutrients added to other variable factors such as the number and types of zinc compounds formed in soil and their solubility to be leached with water.

Another important mineral and heavy metal is manganese (Mn). The leachability of manganese is linked to many factors including the soil type. While it can be easier to leach manganese in acidic soil, only trace levels are leached in alkaline soils as highlighted by studies. The results reveal non-significant differences among treatments for manganese presence with a *p*-value of 0.139. Simultaneously, the average presence levels for manganese in the experimental soil leachates indicate a trace presence with the highest distribution in the control treatment, with a level of 0.02 mg/L, while the treatments with 3, 5 and 7 kg/m² biosolids, respectively, showed manganese levels of 0.004, 0.008 and 0.007 mg/L. The results can be interpreted by considering that the rich contents of organic matter in biosolids minimize the leaching of heavy metals, including manganese [31]. Similarly, the almost-neutral pH of the biosolids produced in Qatar, as revealed by the results, plays a role in lowering the soil pH, which slightly increases the manganese levels in soil as pointed out by [53]. Iron (Fe) is a heavy metal that also interacts with plants and is needed in trace levels [19]. Being a heavy metal with a toxic effect in the case of abundance in soil or groundwater, it is crucial to check its levels in soil leachates gathered from the different treatments in this study. The results reflected non-significant differences among treatments with a *p*-value of 0.514. Furthermore, the average presence of iron in soil leachates revealed a logical sequence by indicating the highest level of iron in the control treatment with 0.13 mg/L, while the treatments with 3, 5 and 7 kg/m² biosolids, respectively, illustrated 0.02, 0.03 and 0.04 mg/L of iron. It was noticeable that the presence of a high amount of organic matter in biosolid treatments acted as a barrier that minimized iron leachability in water, unlike the control treatment with soil only where the leached level of existing iron was slightly higher, as discussed by many studies [49].

The results of the statistical analysis of the leachates indicated non-significant differences versus treatments for aluminum at a *p*-value of 0.814. On the other hand, the highest level was recorded in the control treatment of soil only at 0.48 mg/L. This level was expected as the presence of aluminum in the alkaline quality of soil in Qatar is not high. Additionally, the lack of organic matter will minimize the cation of heavy metals including aluminum and lead, which are leached with water. Nevertheless, the presence of aluminum in the biosolid treatments was not significantly different as the treatment with 3 and 5 kg/m² biosolids revealed aluminum concentration of 0.44 mg/L in soil leachates, while the treatment with 7 kg/m² had only 0.43 mg/L.

Arsenic (As) is an extremely toxic type of heavy metal, which is not soluble in water, but can be found in inorganic forms [12]. The results of soil leachates revealed significant differences among treatments at a *p*-value of 0.093. Subsequently, the average presence in all biosolid treatments had a similar level of 0.02 mg/L, while the control treatment showed 0.01 mg/L only. These results agree with many studies in that the biosolids are rich in heavy metals of different types, including arsenic. However, the comparison with international levels sheds a clear light on the level of potential risk from such a level in groundwater.

Within the same context, both cadmium (Cd) and cobalt (Co) had a slight presence. The statistical analysis highlighted non-significant differences for both types of heavy metals with a *p*-value of 0.532 for cadmium and 0.317 for cobalt. Both heavy metals are insoluble in water, although cadmium salts can be soluble in water, similarly for cobalt [54]. It is essential to highlight that the levels of cadmium and cobalt in soil leachates were very low. However, cadmium indicated almost similar levels for the control treatment and treatments with 3 and 5 kg/m² biosolids, with 0.004 mg/L. In contrast, the treatment

with 7 kg/m² biosolids revealed a cadmium level of 0.003 mg/L. Similarly, the cobalt levels were also trace as the control treatment showed only 0.003 mg/L, while the biosolid treatments showed increased levels: the treatment with 3 kg/m² had a cobalt level of 0.002; the treatment with 5 kg/m² had 0.004 mg/L; and the treatment with 7 kg/m² had the presence of 0.006 mg/L. These non-significant trace levels can be neglected as illustrated by comparing the levels found in the soil with the international levels.

By interpreting these findings, the results show non-significant differences for chromium (Cr) at a *p*-value of 0.486. In contrast, the same analysis highlighted significant differences for nickel (Ni) with a *p*-value of 0.026. Although the levels of these two heavy metals are mostly trace, it worth mentioning that being insoluble in water by nature does not prevent them from being a potential contaminant as there are compounds that possess the ability to be solubilized in water such as chromium oxide and chromium hydroxide or nickel chloride [14]. To obtain a clear perspective on their possible role in contaminating Qatar's groundwater, the results highlighted that the chromium levels were very low, with levels of 0.01 mg/L for control treatment and the treatments with 5 and 7 kg/m² biosolids, respectively. Only the treatment with 3 kg/m² biosolids revealed a chromium presence of 0.002 mg/L. Similarly, the levels of nickel were also trace but with variations, as the lowest presence was in the control treatment with soil only with a level of 0.01 mg/L, while both treatments with 3 and 7 kg/m² biosolids recorded levels of 0.02 mg/L, and the treatment with 5 kg/m² biosolids recorded a nickel level of 0.03 mg/L. These findings may be affected by many factors such as the pelletized formula or the type of soluble compounds formed by these types of heavy metals. Nevertheless, this does not raise the risk factor as it is below the acceptable international levels as further illustrated by comparison.

The same variations are observed with lead (Pb), another important heavy metal pollutant. Lead is a significant pollutant, as it is not soluble in water. The results did not reveal significant differences among treatments for the lead with a *p*-value of 0.441. Simultaneously, all treatments reflected the same level of 0.007 mg/L, which is the minimum level that can be diagnosed by the spectroscopy. This is below the detectable level, which is the actual situation concerning this primary pollutant.

3.6.3. Group 3

Finally, the chemical analysis of soil leachates indicated non-detectable levels for mercury (Hg) and tin (Sn), which can be considered a positive result for biosolid usage. This further reconfirms the biosolids' quality as both elements cause environmental disturbance in many areas around the world due to their toxicity. Subsequently, this gives additional evidence concerning the manufacturers' claim about gathering all treated biosolids of Doha North Sewerage Plant from non-industrial and non-medical areas. It is worth highlighting that the minimum detectable levels by the spectroscopy for mercury are 0.0001mg/L and 0.01 mg/L for tin.

3.7. Leaching Behavior of Pollutants and Nutrients in Biosolid-Amended Soil with Different Rates

The increase in using biosolids as an organic fertilizer has raised several concerns that this study tried to cover in its major parameters in respect to the biosolids produced in Qatar. However, shedding light on the beneficial aspects of using such recycled material should also tackle the risks that might arise from such husbandry practice. One of the main issues might be the leachates from soil fertilized with biosolids. In addition to interpreting the results, it is crucial to highlight the leachability ratio along with how and why to understand the mechanism and action of such nutrients, pollutants and the scientific reasons behind leachability variation, as well as to specify the best practices that help to minimize the hazards of heavy metals and assess their potential impact on groundwater in the future.

Table 7. Comparison of leaching rate for different biosolid treatments for nutrients in soil against the same parameters in leachates.

Treatments	N2 (mg/kg)	N2 Mg/ L	NO3 mg/kg	NO3 mg/L	P mg/kg	P mg/L	B mg/kg	B mg/L	Ca mg/kg	Ca mg/L	Mg mg/kg	Mg mg/L	K mg/kg	K mg/L	Zn mg/kg	Zn mg/L	Mn mg/kg	Mn mg/L	Fe mg/kg	Fe mg/L
T1—3kg Biosolid + Soil	2.17	12.71	22.67	7	1.43	1.87	3	0.24	75.79	40.91	4.99	20.92	794.64	−0.75	72.71	−0.006	4.99	−0.016	3.03	−0.11
T2—5kg Biosolid + soil	2.00	16.14	29.33	11.67	1.50	2.39	3	0.36	68.69	−93.05	5.20	34.71	844.55	1.49	80.74	−0.003	5.20	−0.012	2.61	−0.1
T3—7kg Biosolid + Soil	2.00	31.05	36	22	1.85	1.91	3	0.39	61.26	−31.76	4.82	44.98	788.21	5.85	88.42	−0.006	4.82	−0.013	3.65	−0.09
T4—Control Soil only	2.43	6.07	24	4.33	1.28	0.21	4.52	0.62	74.03	380.62	4.31	21.51	717.60	4.61	36.60	0.009	4.31	0.02	1.77	0.13

Table 8. Comparison of leaching rate for biosolids' heavy metals in soil against the same parameters in leachates.

Treatments	As mg/kg	As mg/L	Cd mg/kg	Cd mg/L	Co mg/kg	Co mg/L	Cr mg/kg	Cr mg/L	Ni mg/kg	Ni mg/L	Pb mg/kg	Pb mg/L	Na mg/kg	Na mg/L	Cu mg/kg	Cu mg/L	Hg mg/kg	Hg mg/L	Al mg/kg	Al mg/L	Sn mg/kg	Sn mg/L
T1—3kg Biosolid + Soil	2.02	0.01	0.31	0.00	3.01	0.00	11.38	0.01	14.31	0.01	2.63	0.01	0.52	−4.66	114.03	11.00	0.01	0.00	4.16	−0.04	1.40	0.01
T2—5kg Biosolid + soil	2.44	0.01	0.31	0.00	3.77	0.00	12.94	0.00	15.47	0.02	2.79	0.01	0.44	−15.31	345.50	13.34	0.01	0.00	4.03	−0.04	1.76	0.01
T3—7kg Biosolid + Soil	1.55	0.01	0.50	0.00	2.84	0.00	14.24	0.00	14.12	0.01	3.39	0.01	0.62	−14.78	347.94	15.78	0.01	0.00	3.84	−0.05	2.08	0.01
T4—Control Soil only	1.52	0.01	0.30	0.00	2.28	0.00	10.33	0.01	12.06	0.01	1.98	0.01	0.63	16.49	95.08	0.02	0.01	0.00	3.45	0.48	1.00	0.01

The leachate can be considered as a mirror of all the reactions in the soil [15]. It gives an idea pertaining to the leachability rate in biosolid treatments compared to the control treatment, which consists of soil only. The difference between the leachates of treatments with biosolids and the control treatment leachates shows the leachability from biosolid material as an additive that needs to be tested, as well as the other variable factors in this study. Simultaneously, the presence level in soil can be another key tool to assess the leachate levels; these main ideas are addressed in comparison Tables 7 and 8, where Table 7 highlights the differences of each pollutant in the leachates between the actual discovered levels in biosolid treatments and the control treatment of soil only. In other words, if the level of each parameter in the biosolid treatments is higher, then the difference shall be highlighted in a positive figure; by contrast, if the control treatment gained a higher level, the figures will be negative (–). Similarly, Table 8 shows the comparison between the discovered level of pollutants in the soil and the level of the same mineral in leachates. In summary, both tables show the link between soil and soil leachates along with the leachability rate of each mineral for a better understanding of the results. The results show strong evidence concerning leachability rates and the overall role of biosolids in the soil for both nutrients and pollutants or heavy metals, as the mobility of such contaminants must be specified in order to create a plan to manage it [20]. The leachability rates are specified in Table 7 and allow us to identify three groups of leaching rates based on comparison against the leachates of the control treatment, which consists of soil only. The first group shows a positive leaching rate, which, as described above, means it has a higher concentration than that of the control treatment as was the case for total nitrogen, nitrate, total phosphorus, boron, magnesium and copper. However, the second group shows a negative leaching rate below that of the control treatment for elements such as potassium, zinc, manganese, iron, aluminum, cobalt and sodium, while the leachates in the third group were below the detection level, such as mercury, tin, lead and cadmium. These variations need to be tackled in depth to understand the nature of the reactions created due to the addition of biosolids. The process specified in this study should be followed by taking a holistic perspective for the obtained results; thus, another comparison in Table 8 was added to compare the discovered rates in soil (mg/kg) and the leachable rates for the same parameters in leachates (mg/L). All the results are to be read in conjunction with each other to reach a conclusion concerning the leachates.

3.8. The Positive Leaching Group

For the total nitrogen in the soil, the control treatment recorded a slightly higher presence (2.43 mg/kg) compared to biosolid treatments. However, all the biosolid treatments showed higher leachability rates than the control treatments. These important parameters indicate that the total nitrogen was subjected to many reactions that create such variability. In particular, by the soil microorganisms' nitrifying and denitrifying bacteria where the soil enriched with biosolids can logically be expected to be a good environment for these organic matter-associated bacteria as the rich contents of biosolids stimulate this type of microorganisms to function actively and adequately, affecting the level of nitrogen in the soil [32,55]. Furthermore, the plants' high utilization of nitrogen as a nourishing element for growth was reflected in the level of growth achieved in the biosolid-treated petunia plants compared to control treatment based on the utilization of the principal amount of nitrogen to enhance the growth rates, as highlighted in the interpretation of the plants' characteristics [56]. Above all, the total nitrogen indicated a high positive leachability rate with irrigation water compared to the control treatment. It is essential to highlight that the test was conducted after three months from the starting date of the experiment taking into account the formula of class A pelletized biosolids, which are designed to ensure a slow release of elements [57]. Therefore, three months were also meant to allow the pellets to be homogenized and melted before gathering the data. Simultaneously, these results mean that nitrogen levels were much higher in the biosolid treatments at the initiation stage of the experiments. However, the optimization processes led by soil microorganisms' activities, plant utilization of nitrogen and positive leaching rates all worked synergistically to

minimize the nitrogen levels. The same can be said concerning the other forms of nitrogen such as nitrate, which reflected a positive occurrence in both soil and leachates (rather than only in the control treatment) and can be considered as subsidiary evidence that reinforces this conclusion and shed lights on the type of reactions of such main parameters in both soil and leachates. The results also highlight the positive presence of total phosphorus in both soil and leachates compared to the control treatment, which is expected since biosolids are known to be rich organic fertilizers with several types of nutrients, as discussed by many studies [27]. Subsequently, as the second most crucial element for plant growth, the study can rely on the excellent and steady growth that appeared in petunia plants as specified by the tested biological parameters to conclude that a fair amount of phosphorus was utilized by the plants to thrive. Moreover, the trace presence of phosphorus in leachates can be attributed to the pelletized form of biosolids that slows the nutrients' release [58]; this is in addition to the strong binding nature of phosphorus with soil particles and organic matters, as highlighted by many studies [27,59]. On the other hand, the heavy metals of boron, magnesium and copper also showed a positive reaction. These important elements are required by plants in trace amounts [60]. The study highlighted several issues. The first and most important is that all the discovered levels of them were well below the international acceptable limits of pollutants, as highlighted in the comparison in Table 5. Similarly, growth monitoring and the analysis of biological parameters did not reveal any signs or symptoms of deficiencies in petunia plants, which means that the steady and stable growth was moving smoothly due to firm and continuous supply of these microelements that were utilized is indicative of the role of biosolids' presence in soil and the leachability rates. The compatibility between the presence of these elements in the soil and the leached rates was obvious; for instance, the level of boron in the control treatment soil was higher than the level recorded in the biosolids treatment soil (4.52 mg/kg compared to 3.0 mg/kg). The same continued to appear in the leachates, and this was also the case for copper and magnesium. Although these levels are below the international limits, it is still crucial to highlight that maintaining good production practices ensures the suitable usage of biosolids for other environmental components such as soil and groundwater.

3.9. The Negative Leaching Group

This group consists of potassium, zinc, manganese, iron, aluminum, cobalt and sodium. The word negative refers to the differences between the concentration of the element in the leachates of the biosolid treatment and the concentration of the leachates in the control treatment for the same elements, which have a minus sign (-). In other words, the presence of biosolids had a negative impact on the levels of these elements in leachates for many reasons that we shall elaborate after discussing these levels. Despite this, not all treatments indicated a negative presence, but it still contains a negative impact. For instance, the 3kg/m² biosolids treatment reflected the second-highest level of potassium (K) in soil with 794.64 mg/kg, which is higher than the control treatment of soil only for the same parameter (which revealed 717.60 mg/kg). However, the same treatment showed a negative presence against the control treatment in leachates: 0.75 mg/L compared to 4.16 mg/L for the same parameters in leachates. The results might be more informative when the description is provided that a similar situation took place for other parameters such as zinc, manganese, iron, aluminum, cobalt and sodium. Therefore, questions were raised concerning the reason behind these. Hence, to justify such variances correctly, a study on related tasks associated with the production process and the chemical properties of the material of class A biosolids had to be conducted to find proper answers to shed light on the experiment. It is important to highlight that the sludge passes through several production steps before reaching the field as a pelletized biosolid. The main idea is to digest the sewage product after dissolving in water and make it more stable for use [58]. This step comprises many stages such as aerobic digestion and thermal treatment at higher levels to ensure a sufficient level of sterilization and to manage the presence of harmful biological agents such as bacteria and fungi [14] before starting the dewatering or drying process, which

includes adding lime to the biosolid to minimize the moisture content [27]. Studies have pointed out the importance of the formulation type of biosolids to stabilize and control the hazards from using it as an organic fertilizer [1]. Simultaneously, the literature indicates that the pelletized formula is the most suitable for several reasons such as minimizing the dust on-site and the simplicity of mixing it with soil particles [57]. However, this process incorporates a densifying technology to form the product into pellets by molding it with moldy lime as a strong binder that maintains the shape and offers the privilege of turning this stabilized material into a slow-release fertilizer without an adverse impact on the environment [14]. Such methodology leads to the specific description of such material as of EQ, or exceptional quality, which can be used freely without restrictions [57]. The concept was based on the idea that such formulation type will not be a potential cause of environmental nuisance, or, it will be more suitable for use and without possible detrimental impacts on environmental aspects including the groundwater. Hence, the formula of class A biosolids can be translated into gaining the desired results. Additionally, the high content of organic matters in such recycled products has an imminent advantage by catching and binding many of these pollutants, especially heavy metals [49]. This works as a safety layer that minimizes the level of pollutants from being leached into groundwater. The reasons behind their absence can be easily recognized: the pelletized formula and the catching of heavy metals work synergistically to optimize the level of pollutants. Similarly, the literature also revealed that sandy soil's texture acts as another screen that filtrates the heavy metals via firmly binding them with the soil particles [51]. It worth mentioning that the levels of mercury, lead, tin and cadmium were scarcely below the detected levels in the leachates, as indicated from the chemical analysis of soil leachates and interpretation of the results.

3.10. Comprehensive Discussion of Biosolid Soil Leachates

Groundwater is one of the major sources of water for drinking, agricultural and industrial purposes around the world [57]. Geographically, Qatar is a peninsula with a very low yearly average of rain (76 mm). Furthermore, there are various types of soils, which are mainly the lithosol type of limestone rocks and sandy calcareous soil [8]. The remaining types of soil consist of the common Lusabkha soil, which is a salty type and lies mostly in the coastal areas. It is a barren type of soil that is not suitable for agriculture, and few other locations that are commonly known as Rowda are utilized for agricultural purposes [59]. Rain is the main source for replenishing the groundwater. In addition to being low, rain is also a variable with a higher frequency in the north, decreasing toward the south [59]. Groundwater has been excessively utilized in Qatar over many decades as it was the only source for agriculture and domestic uses before 1960 [60]. Groundwater remains to be used for agricultural purposes only. Such intensive utilization in the past has affected both the quantity and the quality as it became susceptible to contamination from the usage of anthropogenic fertilizers. Biosolids, as a new product in the Qatari environment, deserve to be studied as they are well known for their rich contents of nutrients and pollutants. Thus, this part of the study was designed to determine the level of pollutants in the soil leachates and interpret the results by a comparison set against the international standards. The results indicate that the levels of pollutants in biosolid treatments are well below the international standards in a way that allows the conclusion that there will not be any significant harmful effects on the groundwater in Qatar from the leached water of soils fertilized with biosolids for several reasons:

- (1) All plantations in Qatar, whether they are for agricultural or landscaping purposes, are mandatorily irrigated by modern irrigation devices such as bubblers or drippers, which ensure a slow and minimal discharge according to the plants' needs within the topsoil or at the root-zone area without any excessive flowrate that can penetrate the soil deeply towards the aquifers or groundwater areas. This is part of Qatar's arrangements to preserve the limited sources of water and to enhance irrigation efficiency [9]. Most of the groundwater areas which are utilized for agricultural purposes lie in the northern part of the country at a depth of between 60 and 70 m [46],

making it almost impossible to be subjected to any leachates, especially with the low flowrate and sharply calculated daily irrigation figures, which are also minimized with the high evaporation rate in the harsh summer in Qatar.

- (2) The results highlight good levels of the major nutrients such as N, P and K along with other trace elements, which is essential for enhancing the barren type of soil in Qatar and promoting the vitality of soil microorganisms and the native flora of the desert. These advantages gained from using a recycled material such as municipal biosolids are the core of sustainable practices that far outweigh the disadvantages such as the contents of heavy metals, especially since the discovered levels of pollutants were all below the international acceptable levels according to the chemical analysis of both the soil and leachates.
- (3) Qatar's soil type, rich in sandy loam, and sandy calcareous soils with different layers can be considered a shield against leachates' penetration into deeper areas. For all the reasons mentioned above and due to Qatar's high-quality biosolids, it can be stated that the hazards and risk factors from contaminating the groundwater in Qatar by biosolid leachates are minimal [61]. This conclusion is in accordance with the strict regulations for the suitable and non-harmful application rate. Subsequently, this is also subjected to maintaining the good quality of biosolids and refraining from applying the old concept of landfills to prevent accumulating large quantities of biosolids in a particular area and increasing the risk of leaching the residues of leachates to the aquifers [62].

4. Conclusions

An experimental study was performed to evaluate the use of municipal biosolids in soils for ornamental plant cultivation. The first step was conducted to evaluate the biosolids produced in Qatar and their usage as an organic fertilizer to fertilize ornamental plants. Specifying the ideal application rate of biosolids with *Petunia atkinsiana* as the experimental plant three different application rates of class A biosolids were tested (3, 5 and 7 kg/m²) along with a control treatment of soil only. The treatment took three months, and the morphological parameters that were investigated included plant height, stem diameter, number of leaves, width and length of the leaves and the number of flowers. In summary, based on the outputs of the results and monitoring process, the study highlighted that the biosolids proved to be appropriate organic fertilizers for ornamental plants, while the application rates of 5 and 7 kg/m² being successful to develop plants' vegetative growth and flowering with the rate of 5 kg/m² showing optimal results. The control experiment was last in almost everything, followed by the treatment with 3 kg/m², which was second in stem diameter and leaf length, as shown in Table 1. In conjunction with the analysis of plant characteristics, the chemical analysis of soil revealed promising results regarding the level of important nutrients such as nitrogen, phosphorus, potassium and contaminants like heavy metals. Furthermore, other parameters that were investigated included the PH value, organic matter, total salt, sodium adsorption ratio (SAR), free carbonates, chloride content, sulfates, nitrates, calcium, magnesium, potassium and phosphorus. By contrast, the highest discovered level was well below the regional and international allowable limits, as highlighted in the discussion and comparison tables. The study confidently nominated the levels of 5 and 7 kg/m² of biosolids as efficient and safe rates of application to enrich the Qatari soils, which are to be considered safe in terms of the different experimented parameters regarding pollutants. The other targets of this experimental design are to investigate the potential impact of all tested application rates on groundwater by analyzing the soil leachates. The results of the chemical analysis have been well explained and can be affirmed in Tables 7 and 8. The third part of this study was also chemical analysis, with a focus on biosolids' soil leachates. The parameters experimented here include the pH of the irrigation water, total salts, total nitrogen, chloride content, sulfates, nitrogen, nitrate, total phosphorus, potassium, calcium, magnesium, sodium and heavy metals. The results indicate that the levels of pollutants within the leachates are well below the international standards, allowing the conclusion that there will not be

any significant harmful effects on the groundwater in Qatar from the leached water of soils fertilized with biosolids. A further part of this study focused on the leaching behavior of pollutants and nutrients in biosolids adjusted to different rates. The results of this study can be confirmed in Tables 7 and 8. This study also involved classifying the positive leaching group, which consisted of total nitrogen and nitrate, total phosphorus, boron, magnesium and copper. On the other hand, the negative leaching group included potassium, zinc, manganese, iron, aluminum, cobalt and sodium. Furthermore, there was another group of non-detected pollutants within the soil leachates.

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