agronomy

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Investigating the Quality and Efficiency of Biosolid Produced in Qatar as a Fertilizer in Tomato Production

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Abstract: This study evaluated biosolid quality over time and the efficiency of using amounts (5 and 7 kg/m^2) of municipal class A biosolids in Qatar to fertilize tomato plants (*Solanum lycopersicum*). Random samples were subjected to physical and chemical analysis, which revealed excellent particle uniformity and stability with minor odor defects. The analysis confirmed the product was nutrient-rich while pollutant levels were below the international standards. The nominated rates were used to fertilize tomato plants in pots grown in a greenhouse for four months with a control treatment of manure and Peat-Moss, before measuring the plant biological characteristics. Plants were examined via chemical analysis of nutrients and pollutants both for the whole plant and for stems, fruits, and leaves. Results indicated that both experimental treatments enhanced plant growth and development as compared to the control treatment. However, the chemical analyses also revealed levels of zinc, copper, and manganese in the plant fruits that were well in excess of the maximum acceptable levels, as defined by international health organizations. This study found that while the application of class A biosolids as organic fertilizer for tomato plants greatly enhanced the overall plant growth, the plant fruits contained toxic levels of trace heavy metals.

Keywords: biosolids; agriculture; tomato; waste management; manure; heavy metals

Citation: Ali, M.; Ahmed, T.; Abu-Dieyeh, M.; Al-Ghouti, M.A. Investigating the Quality and Efficiency of Biosolid Produced in Qatar as a Fertilizer in Tomato Production. *Agronomy* **2021**, *11*, 2552. https://doi.org/10.3390/agronomy11122552

Academic Editors: Othmane Merah, Purushothaman Chirakkuzhyil Abhilash, Magdi T. Abdelhamid, Hailin Zhang and Bachar Zebib

Received: 3 November 2021
Accepted: 13 December 2021
Published: 15 December 2021

1. Introduction

The necessity of developing agriculture has become a requirement in recent decades as a way to cope with population growth worldwide. The deterioration of arable lands and the excessive usage of pesticides and agrochemical fertilizer, along with the related dynamic factors such as climate changes, are the reasons behind many global catastrophes [1]. There are signs of our success in managing some of these catastrophes as well as signs of our failures in many more. Such imbalance has motivated scientists to look for more sustainable methods to mitigate the adverse impacts on the environment without slowing down agricultural development. This has led to the initiation of a modern take on an ancient concept, that of organic farming. Organic farming generally refers to the application of natural, environmentally friendly solutions according to agricultural best practices to gain a healthier yield. Setting aside the different connotations and uses of the term "agricultural farming", for the most part, it refers to the use of organic fertilizers of different kinds, including those based on biosolids. The incorporation of sewage products into agricultural practices has gained traction in many parts of the world. Scientists and researchers have influenced rules and regulations for this application by proposing new methods of sewage treatment, specifying the application rate, choosing certain types of crops to be fertilized, arranging for tests, and evaluating the potential impacts on the environment and human health as part of a holistic approach [1]. The use of biosolids as organic fertilizer has also gained popularity as a sustainable approach for enhancing soils toward increasing crop yields as well as to meet the increased demand for urban greenery programs. Biosolids are described as processed sewage sludge, specifically dried pellets, which is one of the primary byproducts of wastewater treatment plants [2]. However, certain issues remain that restrict promoting its use in agricultural practices [3]. Quality is one of the most important factors that needs to be considered in the sludge industry, which includes its chemical and physical characteristics [4]. Additionally, the levels of nutrients and pollutants in sludge can be an issue [5], for which their degree of stability and how they were produced are relevant [6]. All these factors are highly important when assessing sludge quality [7]. Most studies have attempted to investigate the core problem by assessing the quality of sludge in terms of its chemical and physical characteristics to determine its effectiveness as a fertilizer and soil modifier. Such studies have often tested two proposed pivotal hypotheses: the first concerning the characterization of the produced biosolids in certain areas in terms of their levels of nutrients and pollutants and whether they meet international standards, and the second concerning the assumption that the method for biosolids production, such as that of the Public Work Authority PWA in Qatar, is efficient and, thus, has no major deficiencies concerning the aforementioned issues.

Agriculture is a strategic sector that plays a vital role in all economies. Its scope is not restricted to food production and security and goes well beyond just the production of many raw materials for other industries [8]. The success of agriculture is dependent on many basic requirements: fertile, arable lands; harvesting technologies; irrigation infrastructure; and production needs such as labor and capital to increase yields [9]. During ancient times, settled communities developed various tools and equipment for enhancing agricultural production, some of which are still used today [10]. One of the most significant farming practices involved the use of sludge as fertilizer, which is organic by nature. Trial and error have guided farming cultures worldwide in sourcing a variety of organic fertilizers, depending on the available local resources [11].

Many sources of organic fertilizers are used in agriculture today. There are animal-based biomasses, including livestock manure, guano, and other byproducts of meat-processing industries [12].

Urban settlements have achieved economies of scale in recycling domestic sewage and septage in the form of sewage sludge, which is then harvested as a sustainable means of waste management. Angin et al. [13] showed that biomass from plant matter, such as compost, peat, and crop residues, is another product of recycling.

Farmers in ancient civilizations used sludge as fertilizer. Records indicate that the inhabitants in Mesopotamia (Iraq) developed a city-scale sanitary system to process human excreta and recycle it for use in farming [14]. Similarly, ancient Egyptians used the "basin technique" to treat sludge and make it suitable for application in agricultural practices [15]. This process of primitive recycling was also practiced globally as the historical evidence has confirmed that farmers followed similar practices in China and India during the 18th century [16]. Human waste was similarly regarded as animal waste, a rich source of nutrients beneficial to crops, and served as a backbone of ancient cropping systems in nations such as Mesopotamia, India, and China [17]. Due to increasing urbanization, the use of sludge as an organic fertilizer became globally accepted to address the twin objectives of managing waste and generating a useful resource in a cycle [13–17].

The treatment of wastewater and the production of sludge as a byproduct has evolved into modern and more sophisticated methods of stringent sanitation standards that are mostly the responsibility of municipal sewage services. The treatment services have become necessary components of both waste disposal and green infrastructure to accommodate the increasing sludge quantities generated by urban populations [18]. The resulting byproducts of treated sewage effluent (TSE) are a useful resource for both urban greenery programs and agricultural production, which include the sludge products and biosolids indicated earlier [17]. In the interest of sanitation, governments have imposed standards in which multiple treatments of wastewater are required, involving either aerobic or anaerobic digestion, along with physical solid dissolution and purification, chemical treatment, thickening, dewatering, and thermal treatments in addition to numerous other efficient modern techniques for enhancing sludge quality [19]. In 2017, it was estimated that the sewage treatment services generated 46 million tons of product in China for agricultural purposes, 2 million tons in Germany, and 7.7 million tons in the United States [18]. According to a follow-up study conducted by Liu and Yao [20], sewage treatment services generated the targeted amount in terms of tons of products to be used for agricultural purposes. It seemed countries around the world wanted to handle this problem efficiently and effectively and, therefore, expanded technologies to handle sludge and realize benefits. This has encouraged the use of wastewater management plants for agricultural or landscaping purposes as a worthwhile expansion of management technologies [19]. The practice has also minimized toxic waste and satisfied hygiene safety. The use of sludge byproducts in Europe's mature industry has long been socially accepted, with communities served by sewage treatment plants in Denmark, Sweden, Netherlands, and Luxembourg [19]. The EU population generates 420 million tons of waste, and only 50 tons are recovered as potential energy. The remaining quantities are used to produce organic fertilizers or as organic matter [21].

Using sludge as a conditioner to enrich soil because of its nutrient contents (e.g., nitrogen, potassium, and phosphorus) in gardens and parks has become commonplace [17]. Notable examples include the Stockley Park in London, where a 100-hectare derelict site was converted to an award-winning golf course. Nevertheless, the business park had its soil formulated in situ from suitably textured mineral material found onsite and conditioned with 100,000 m^3 of air-dried sludge [22]. Approximately 62% of the total quantities of sludge in the UK are currently recycled for use in agricultural land, but laws have restricted the use of sludge as fertilizer. Without even considering these legal limitations, the present challenge remains more focused on how to organize the process, rather than to avoid using sludge as fertilizer [23].

For instance, in the Middle East, the large-scale use of sludge on land is not well established. This may be explained, in part, by social resistance, though poor-quality sludge and sludge producers who find landfill disposal a cheaper and more accessible outlet have certainly contributed to the reticence [24]. In Abu Dhabi, the capital of the United Arab Emirates (UAE), solid waste biomass and sludge are composted together and widely used by parks and gardens departments for landscape maintenance [21]. Nevertheless, farmers tend to be cautious about initial usage where the experience has been limited. However, there are examples of highly successful and widespread use of sludge, such as in Egypt, where the practical demonstration of the value of sludge rapidly overcame any social resistance and unlocked a sizeable latent demand for converting a disposal activity into a revenue stream [25]. In the last half of 2017, Qatar started using class A biosolids as organic fertilizer and for soil amendment as part of its green infrastructure goals in public spaces (e.g., public parks, open spaces, and streetscapes) [26]. While recognized as a sustainable practice, the use of sludge in Qatar's public spaces was considered a pioneering initiative in addressing the dual concerns of cycling back a renewable resource, such as waste, while increasing the footprint of its urban greenery.

Studies on treating wastewater and sludge are fundamental for scaling the quality of biosolid byproducts according to international standards. Many researchers have been investigating the effective use of sludge and its byproducts in the agricultural sector. However, this has not been an area of focus in Qatar, which means research is necessary to identify how efficiently biosolids can be utilized for better agricultural activities in the country [24]. The government of Qatar has been promoting the use of organic fertilizers in crop production. Currently, the government has constructed and commissioned a thermal dryer plant at Doha North Sewage Treatment Works (DN STW), which produces both class A and B biosolids. However, the government has only approved the use of class A organic fertilizer for landscaping and ornamental plants. Research has shown that the effective use of sludge as authorized by the Qatari government could promote crop production and better lives for urban dwellers [27].

A study conducted by Ryan et al. [28] revealed that biosolids consist of nutrients such as 5.5% nitrogen and 2% phosphorus in addition to dry solids, organic matter, and trace elements including zinc, copper, and iron in addition to undesirable heavy metals such as lead and mercury. The use of biosolids as an agricultural fertilizer has been regarded as the most sustainable practice as the material can be 100% recycled [28]. Furthermore, studies conducted by Association of Official Analytical Chemists [29] also pointed out that sludge significantly enhances soil properties by slowly releasing fertilizer, hence ensuring the availability of nutrients throughout different stages of plant growth. Likewise, it promotes the growth of beneficial soil microorganisms, soil structure, and aeration [24]. Despite all the restrictions of social resistance and governmental rules and regulations, the successful use of biosolids as organic fertilizer for specific plant categories has not restricted its usage in other types, including edible crops, in the future. To reach such a level of improvement will require a deeper understanding of this product to assess the quality of biosolids and its role in improving soil fertility in addition to estimating the possible effect on human health and the environment. Researchers should consider these as critical elements for assessing the possible consequences of biosolid use as an organic fertilizer for edible plants. This study was conducted to evaluate the quality of biosolids produced in Qatar and investigate their suitability as an organic fertilizer in the production of edible fruits.

2. Materials and Methodology

2.1. Biosolid Quality

The first step involved the random collection of four bags of freshly produced biosolids, each weighing 10 kg, at three-month intervals (i.e., 3 February 2018, 3 May 2018, and 3 August 2018) using the recommendations of Qatar construction specifications [30]. Samples, representative of the material were packaged with labels indicating the material type, date produced, and their source (i.e., Public Work Authority, Doha North Sewage Treatment Plant (DNSTP)). The sample were accordingly analyzed in Doha at a public work authority lab to determine their temporal characteristics.

2.1.1. Physical Analysis of Biosolids

The physical analysis involved determining the particle sizes of the pellets through the mechanical method of sieving after first drying the samples to constant weight in the oven (Genlab brand, Cheshire, UK) at 110 ± 5 °C, using the mechanical sieve shaker (Controls group, Milan, Italy), standard sieves (Impact, Ayrshire, UK), analytical balance (New Jersey, USA), and hydrometer (Brannan, Cleator Moor, Cumbria, UK). A sample of 1 kg of dry aggregate was sieved using sieves of different aperture sizes to determine the particle size distribution [31].

2.1.2. pH and EC

Moreover, chemical analysis was conducted to determine the sample pH value and electrical conductivity by using a standard pH meter (Hach Company, Loveland, CO, USA) and EC meter (Hach, Loveland, CO, USA), respectively, according to American Society for Testing and Materials ASTM by stirring the suspension sample and distilled water before inserting the combined electrode [32].

2.1.3. Sodium Adsorption Ratio (SAR) and Exchangeable Sodium

The sodium adsorption ratio (SAR) was measured according to Richards and Allison in [33] by preparing a saturated paste of biosolid sample and distilled water before applying the equation to calculate the proportion of sodium and allowing the solids to settle for 24 h; the sample was then filtered before the filtrate was analyzed by ICP–OES. Similarly, the exchangeable sodium percentage was determined by adding the biosolid sample to an extracting solution followed by shaking and centrifugation before analysis using the ICAP

Spectrophotometer (Thermo Fisher Scientific, Waltham, MA, USA), with measurement according to the method of Rayment and Lyons described in [34]. The samples were first prepared using a microwave oven. 0.5 g of the soil sample was extracted and dissolved in concentrated nitric acid, under microwave heating with an appropriate laboratory microwave unit. Both the acid(s) and the sample were put in vessel liner or fluorocarbon polymer (PFA or TFM) or quartz microwave vessel. The vessel was vacuum-packed and heated for a specified time in the microwave unit. The vessel was then cooled, and its contents filtered, centrifuged then diluted to volume for chemical analysis using ICP-OES (Inductively coupled Plasma-Optical emission spectrometry). The test was managed by ICAP 7000 Thermo Fisher ICP-OES (Thermo Fisher Scientific, Waltham, MA, USA)

2.1.4. Nitrate NO_3

Additionally, the US EPA 821 method 1685 was applied to measure nitrate (PPM) by mixing the biosolid sample with purified water followed by shaking and the filtering prior to determining the nitrate content using HACH company nitrate reagent [35].

2.1.5. Chloride Content

Parameters of chloride content % were measured using the guidelines of Richards and Alisson by preparing a solution of potassium chromate and silver nitrate, then filtering both added together by pipette and titrated until the first reddish-brown color was observed and the measuring formula applied [36].

2.1.6. Free Carbonate

Furthermore, free carbonate was measured by preparing three chemical reagents of ammonium oxalate by dissolving 12.4 g of ammonium oxalate with distilled water while using NaOH solution to adjust the pH reading to 8.3. The solution was then diluted to one liter, 20% sulfuric acid by adding distilled water to 120 mL of concentrated H_2SO_4 up to one liter, and potassium permanganate by adding 3.16 g of potassium permanganate to one liter and shaking the mixture together with the sample until the color of the solution changed to violet; the calculation formula was applied according to the Manual of Laboratory Routine Analysis for Soil Testing, Water, and Plant Analysis [37].

2.1.7. Organic Matter % (OM)

The organic matter % was determined by following the specifications of Richards, which involved the preparation of ferroin indicator and $FeSO_4$ as well as concentrated H_2SO_4, 1 g of the biosolid was weighed and transferred into a 500 mL Erlenmeyer flask before adding 10 mL of 1 N $K_2Cr_2O_7$, then constantly and gently swirling the flask to dissolve the soil in the solution. 20 mL of concentrated H_2SO_4 was added into the suspension, and again gently swirling the flask for one minute until the reagents and the soil was mixed. The mixture was allowed to stand for about 30 min. An addition of 200 mL of distilled water was added to the flask then ten drops of the indicator were dropped into the solution. The solution was then titrated with 0.5 N $FeSO_4$ until the color changed from green to red. The organic matter percentage was calculated by applying the formula in [38].

2.1.8. Total Nitrogen, Available Phosphate, Total Phosphorus and Heavy Metals

The semimicro-Kjeldahl method, according to Rayment and Lyons [34], was used to specify the total nitrogen. The remaining parameters of available zinc, available phosphate, total phosphorus, and heavy metals were measured using optical spectrometry (Thermo Fisher Scientific, MA, USA) to assess the characteristic emission spectra after digesting and filtering the sample as per EPA guidelines [39].

2.2. Experimental Design

2.2.1. Biosolid Treatment

Prepared soil textures were mainly dune sand from the same batch acquired from approved government sources as per Qatar construction specifications [30]. The treatment comprised a mixture of soil additives with two different rates of 5 and 7 kg/m^2 of class A biosolid, while the control treatment comprised 5 kg/m^2 of thermally treated manure plus 20 L/m^2 of peat moss as regularly used in Qatari projects. The mixing process was conducted using a standard wooden square before planting tomato plants in 40 cm pots. Treatments were continuously monitored in a controlled environment under the varying temperatures of 25–27 °C. The pots were incubated in the greenhouse at the Qatar Foundation from November 2017 to March 2018 (4 months total) to allow the biosolid pellets to homogenize and dissolve.

2.2.2. Cultivation of Tomatoes

The tomato plants were 20 cm in overall height (OVH) and had eight leaves each. The daily irrigation levels were controlled using a central irrigation system (Motorola, Dallas, TX, USA), and the flow rate varied between 1.5 L per day in November 2017 and up to 2.5 L/day in March 2018 [7]. All the samples were subjected to qualitative and quantitative analysis. After four months

2.2.3. Morphophysiological Analysis of Tomatoes

The plant characteristics including stem girth, height of plants, leaf width, and length as well as the number of leaves and density of fruits produced for each treatment were measured using a digital Vernier scale and standard measurer. All the recorded data were subjected to statistical analysis for better assessment of the potential impacts of biosolids on tomato plant growth.

2.2.4. Chemical Analysis on Tomatoes

The preparation of plant and fruit samples took place in the laboratory, in which the plant tissue was cleaned and the pesticide, dust, and fertilizer residue removed by rinsing with deionized water to wash the plants or by rinsing with 0.1–0.3% P-free detergent and then deionized water. This step was followed by the halting of enzymatic activity by drying samples in an oven at 65 °C for 24 h. After that, plant tissues were mechanically ground to produce a material appropriate for further assessment. Prepared samples were passed through a 60-mesh sieve to obtain a constant particle size before samples were subjected to chemical analysis. Determination of dry matter % for tomato plants (*Solanum lycopersicum*) was carried out according to the method by the Association of Official Analytical Chemists, which involved using an oven to dry the sample and evaporate the moisture to produce dry matter suitable for analysis by the gravimetrical method and applying the calculation formula [29]. Subsequently, determination of total nitrogen in the tomato plant included using a micro-Kjeldahl apparatus (Gerhardt GmbH, Königswinter, Germany) and chemical reagents such as Tashiro's indicator and boric acid indicative solution before applying the calculative equation according to the Manual of Laboratory Routine Analysis for Soil Testing, Water, and Plant Analysis [37]. The total phosphorus in tomato plants was managed with three major chemical reagents, ammonium molybdate–vanadate in nitric acid, phosphorus standard stock solution, and phosphorus working standard; the samples were digested and filtrated before measuring the percentage of transmittance at a wavelength of 410 nm on a spectrophotometer, according to the method described by Ryan et al. [28] while the Manual of Laboratory Routine Analysis for Soil Testing, Water, and Plant Analysis [37] method was used to measure the potassium in tomatoes by preparing potassium standard stock solution and the working standard. While the plant materials were digested and filtered, the concentration of potassium was measured in the standards and plotted on a graph along with the control samples (R) before applying the equation. Similarly, Richards's method [38] was utilized to measure the calcium and magnesium in the plants by preparing the samples with chemical reagents before filtration and calculation of each element via applying a specified equation. Lastly, the plant parts were digested and filtrated according the method described by the Association of Official Analytical Chemists [40] before using an ICP emission spectrometer to analyze and measure the heavy metals in plants with parameters for power of 1.1 kilowatts, and the specified reflected power was <10 watts. Consequently, the aspiration rate was 0.85–3.5 mL per minute, and the flush between test solutions was 15–45 s with an integration time of 1–10 s.

2.3. Statistical Analysis

Treatments were subjected to statistical analysis using a randomized complete block design (RCBD). The efficiency of biosolid production via temporal intervals and its consequences on growth of tomato plants and pollutants levels for two different rates of biosolid application were investigated using analysis of variance. In addition, paired means comparisons were applied via Tukey's test, where the *F*-test pointed out the significant impacts at the degree of $p < 0.05$. Furthermore, the statistical analysis of the results was generated using the general linear model with Minitab software (Minitab, Inc., State College, PA, USA).

3. Results and Discussion

3.1. Biosolid Quality

3.1.1. Physical Characteristics

As highlighted in Table 1, the sieving tests revealed the general consistency of the product in terms of particle size. One hundred percent of the dried pellets from all the samples passed through sieve apertures of 75, 63, 50, 37.5, 25, 19, 12.5, 9.5, and 4.75 mm, which complied with PWA specified standards of 75 mm. In total, 93.26% of the particles were within the range of 2–44 mm in size, with an average particle size of 3.6 mm [7]. Meanwhile, the hydrometer analyses for the particles less than 2 mm reflected almost identical results, where sand particles represented 98.33% of the total portion, and the remaining particles were silt and clay. Furthermore, a highly objectionable odor emanated from all the samples, indicating a disruption in the odor-treatment unit as it lasted for more than a week. In practical applications, such issues with organic fertilizers will require insurance for public nuisance, which will need to be managed by producers.

Table 1. Average Results of Sieves and Hydrometer Analysis for Biosolid Particles.

Sieve Size (mm)	Percentage Passing by Weight		
	Sieve Analysis Mean for Sample 1	Sieve Analysis Mean for Sample 2	Sieve Analysis Mean for Sample 3
75.000	100.0	100.0	100.0
63.000	100.0	100.0	100.0
50.000	100.0	100.0	100.0
37.500	100.0	100.0	100.0
25.000	100.0	100.0	100.0
19.000	100.0	100.0	100.0
12.500	100.0	100.0	100.0
9.500	100.0	100.0	100.0
4.750	100.0	100.0	100.0
2.000	9.0	6.0	5.2
0.425	2.1	1.4	2.2
0.075	1.9	1.0	2.1
Hydrometer Analysis	Sample 1	Sample 2	Sample 3
0.020	1.2	0.8	0.8
0.005	1.5	0.4	0.4
0.001	0.0	0.2	0.2

3.1.2. Chemical Characteristics

In the chemical analysis, as highlighted in Tables 2 and 3, significant differences were noted in pH versus treatment, with $p = 0.004$. However, the average of each sample showed an almost neutral pH higher than 6.0 with an average range of 6.32–6.5, which plays a pivotal role in reducing the soil pH during cultivation [41]. The electrical conductivity (EC) also reflected highly significant differences with a $p = 0.000$, which had been expected since that potable water in Qatar originates from seawater desalination rather than from groundwater harvesting. Sewage water has additional input that will impact contents [7]. However, the average range of 2.40–4.1 (mS/cm^2) was within acceptable levels, according to the standards of Qatar [30]. The results revealed no significant differences for the sodium adsorption ratio (SAR) among treatments, with $p = 0.58$, whereas the average range between 5.41 and 6.16 did not show excessive concentrations, which would be toxic to plants [42]. The results recorded significant differences for exchangeable sodium levels at $p = 0.003$ and a mean range of 2.43–10.15. Such variability in sodium levels could be attributed to the type of input, which eventually determines the biosolid quality.

It was also confirmed that all forms of nitrogen (N) are essential parameters in assessing the quality of biosolids [43]. The results indicate significant differences for the nitrate level at $p = 0.000$, while the average was within the range of 129.55–398.25 ppm. Moreover, the total nitrogen level indicated no significant differences among treatments, with $p = 0.095$. Similarly, the total average range of nitrogen was 53.9 mg/kg^2. This was particularly significant as biosolids can contain almost 5.5% of nitrogen [7]. The variation in nitrate levels could be attributed to several causes, such as the forming of class A biosolid into granulated pellets, which can influence the rate of NO_3 [44]. Nevertheless, high levels of nitrogen forming in biosolids were reported in many studies [45], which is also negatively impacted by temperature increase [46]. Given these reasons and also considering the efficient thermal treatment of biosolids in the Qatar DNSTP treatment plant, variations were and should be expected, and all measurements should be compared against acceptable international levels before final assessment.

The second major nutrient for plants is phosphorus [43]. The analysis conducted illustrated significant differences for the parameter of total phosphorus with $p = 0.005$ and present within the range of 6.44–29.94 mg/kg^2 according to the average. In addition, inorganic phosphate ions (PO_4) were shown to be an important nutrient for plants, and the results highlighted highly significant differences among treatments at $p = 0.000$ and present at an average value within 158–199.12 mg/kg^2. The variations in the levels of both types of phosphorus were attributed to the variations in sewage inputs because phosphorus is a common component in biosolids, accounting for approximately 2.2% of its content by volume [25]. There are different primary sources of phosphates, including beverages, food residues, and detergents, that enter the sewage stream from source points [47]. Therefore, comparing these results to international standards would be necessary to evaluate the quality of this Qatari biosolid.

Table 2. Analysis of Variance for Biosolid Chemical Parameters.

SOV	DF	Mean Squares												
		pH Value	Electrical Conductivity	Sodium Adsorption Ratio (SAR)	Exchangeable Sodium	Nitrate	Chloride Content	Free Carbonates	Organic Matter	Total N	Total Sulphate Content	Available Phosphate as PO4-P	Available Z	Total P
Treatment	2	0.040 *	3.316 **	0.680	60.060 *	724 **	0.140 **	5.251 **	51.783 **	161	0.0004	317 **	748.29 **	562 *
Error	9	0.003	0.009	1.173	4.857	2450	0.001	0.038	0.432	522	0.001	168	11.62	564
Total	11													

SOV: Sources Of Variations, DF: Degrees of Freedom, * = significantly different (p-value is ≤ 0.05), ** = highly significantly different (p-value is ≤ 0.01).

Table 3. Chemical Parameters means of Biosolid samples with a standard deviation.

Test	Samples of Biosolids Took in February 2018		Samples of Biosolids Took in May 2018		Samples of Biosolids Took in August 2018	
	Mean	**Standard Deviation ±**	**Mean**	**Standard Deviation ±**	**Mean**	**Standard Deviation ±**
pH Value	6.32 ^{B}	0.05	6.32 ^{B}	0.10	6.5 ^{A}	0.05
Electrical Conductivity mS/cm	4.1 ^{A}	0.06	2.40 ^{C}	0.16	3.82 ^{B}	0.02
Sodium Adsorption Ratio (SAR)	5.41 ^{A}	1.18	6.16 ^{A}	1.68	6.08 ^{A}	0.67
Exchangeable Sodium	10.15 ^{A}	1.04	5.82 ^{A,B}	2.20	2.43 ^{B}	2.94
Nitrate mg/Kg	278 ^{B}	48.94	398.25 ^{A}	69.01	129.55 ^{C}	13.82
Chloride Content %	0.46 ^{A}	0.06	0.15 ^{B}	0.03	0.13 ^{B}	0.03
Free Carbonates %	1.09 ^{B}	0.24	0.69 ^{C}	0.16	2.84 ^{A}	0.19
Organic Matter %	59.35 ^{C}	0.96	66.50 ^{A}	0.40	63.59 ^{B}	0.46
Total Nitrogen mg/Kg	52 ^{A}	1.85	54,21 ^{A}	0.37	55,61 ^{A}	3.48
Total Sulfates Content %	0.29 ^{A}	0.04	0.29 ^{A}	0.04	0.27 ^{A}	0.03
Available Zinc mg/Kg	33.45 ^{C}	1.25	50.60 ^{B}	1.60	60.48 ^{A}	5.54
Total Phosphorus mg/Kg	21 ^{A,B}	0.34	29,94 ^{A}	2.39	6.44 ^{B}	15.53

Means comparison was conducted using the Tukey test, and two means sharing the same letter are not significantly different.

Significant differences were found in the results of organic matter (OM) content at $p = 0.000$ and high levels in the range of 59.35%–66.5%, which is a good indicator of the degree of biosolid stabilization [48]. It also suggests the potential of the biosolid to microbial communities with high diversity [49]. Highly significant differences, with $p = 0.000$, were found for other parameters, such as the chloride and free carbonates levels. Such differences had been expected as crude sludge from DNSTP was sourced from non-industrial and non-medical areas [7]. Therefore, water softeners containing sodium chloride (NaCl) from domestic effluent could account for much of the Cl [50]. Variations in such cases could be attributed to the disparities of sludge quality entering the sewage stream from point sources. Similarly, the variability of free carbonate levels should be evaluated while considering that Qatar's soils are predominantly calcareous, and carbonates of calcium and magnesium are dominant [51]. Subsequently, the biosolid production process has required treatment with lime ($CaCo_3$) during thickening and dewatering stages, which potentially contributes to higher and variable levels of free carbonates. Lastly, the total sulfate percentage indicated non-significant differences at $p = 0.726$.

3.1.3. Heavy Metal Content of Biosolids

Undesirable contamination by heavy metals is considered the main disadvantage of using processed sewage sludge [52]. The presence of these heavy metals can indicate the degree of contamination and their impact on biosolid quality [53]. Heavy metals in sewage sludge causes various challenges and limitations where high temperatures in the production process of biosolids have led to the redistribution of heavy metals in sewage sludge through the formation of several different chemical and physical phases [54]. The redistribution of heavy metals is dependent on the sewage sludge characteristics, applied thermal process, and operating conditions. However, there has been incomplete and inconsistent information about the distribution and fate of heavy metals resulting from the various thermal treatment processes due to the limited data available in the literature regarding the comprehensive analysis of heavy metals. The accumulation of heavy metals in sewage sludge is shown to be dependent on the treatment process of wastewater used in treatment plants [55]. An ICP spectrometer was used to determine the heavy metal concentrations for wet biosolids in mg/kg, and the results of the statistical analyses are illustrated in Tables 4 and 5. A highly significant difference in available zinc, at $p = 0.000$, and no significant differences for aluminum, with $p = 0.008$, were found. Additionally, the same was recorded for the potassium (K), with $p = 0.038$, which was the same for all treatments. The statistical analysis of magnesium (Mg) indicated significant differences, as compared to control treatments, with $p = 0.059$, as confirmed by Tukey's pairwise comparison. By extension, sodium (Na) levels reflected substantial differences, with $p = 0.011$. The results were not similar for arsenic (As), chromium (Cr), nickel (Ni), and lead (Pb), with $p = 0.104$, 0.873, 0.671, and 0.252, respectively. A slight variation was found in tin (Sn), which showed a significant difference, with $p = 0.048$. The assessed levels of both nutrients and pollutants were considered very promising in comparison to the regional and international standards or in consideration of acceptable levels of heavy metals. The outcomes therefore allow a positive conclusions to be drawn about the quality of biosolids produced in Qatar.

Table 4. Analysis of Variance for Heavy Metals in Biosolid Samples.

SOV	Mean Squares													
	DF	AL	K	Mg	Na	As	Cd	Co	Cr	Ni	Pb	Sn	Zn	Cu	Hg
Treatment	2	5.4 *	0.87 *	17.78	1.21 *	0.00001	ND	ND	0.000004	0.000007	0.00007	0.000026 *	0.005	7888.7 **	ND
Error	9	0.63	0.18	4.53	0.15	0.000004	ND	ND	0.00003	0.00001	0.00004	0.000006	0.011	205.5	ND
Total	11														

SOV: Sources of Variations, DF: Degrees of Freedom, ND = not detected, minimum detectable level of Cd = 0.2; * = significant differences, minimum detectable level of Co = 0.3; ** = Highly significant differences, minimum detectable level of Hg = 0.01.

Table 5. Mean levels of Heavy Metals in Biosolid samples with standard deviation.

Heavy Metals (mg/kg)	Samples of Biosolids in February 2018		Samples of Biosolids in May 2018		Samples of Biosolids in August 2018	
	Mean	Standard Deviation ±	Mean	Standard Deviation ±	Mean	Standard Deviation ±
Al	5.1 ^{B}	0.37	6.77 ^{A}	1.33	4.54 ^{B}	0.02
K	3.3 ^{A}	0.23	3.45 ^{A}	0.69	2.61 ^{A}	0.12
Mg	11.1 ^{A}	0.96	14.6 ^{A}	3.00	10.76 ^{A}	1.91
Na	3.6 ^{A}	0.39	2.5 ^{B}	0.43	3.015 ^{A,B}	0.36
As	0.002 ^{A}	0.00	0.005 ^{A}	0.00	0.004 ^{A}	0.00
Cd	N.D	-	ND	-	-	-
Hg	ND	-	ND	-	-	-
Co	ND	-	ND	-	-	-
Cr	0.04 ^{A}	0.00	0.04 ^{A}	0.01	0.04 ^{A}	0.00
Ni	0.02 ^{A}	0.01	0.03 ^{A}	0.00	0.02 ^{A}	0.01
Pb	0.017 ^{A}	0.00	0.02 ^{A}	0.00	0.02 ^{A}	0.00
Sn	0.005 ^{A,B}	0.03	0.008 ^{A}	0.16	0.003 ^{B}	0.09
Cu	114.3	0.37	30.57	1.33	46.87	0.02
Zn	0.92 ^{A}	0.23	0.86 ^{A}	0.69	0.86 ^{A}	0.12

Means comparison was conducted using Tukey’s test, and two means sharing the same letter are not significantly different. ND = not detected. Minimum detectable levels of cadmium = 0.2, cobalt = 0.3, and mercury = 0.01.

3.1.4. Comparison of Pollutant Contents against International Standards

Large quantities of biosolids are generated daily, and substantial volumes are recycled as organic fertilizer or soil amendments for agricultural crops or landscaping projects. It is of great concern to determine the levels of potential pollutants in the produced sludge to assess its quality after processing for suitable use. Pollutants, notably heavy metals, are a concern because of their potential to contaminate soils and bioaccumulate through the food chain. Numerous countries and international institutions have determined restrictions and set standards for the quality of the produced sludge and their application rates as well as prescribed mitigating measures for the potential adverse impacts of biosolid use. The prevailing international standards and levels vary and are country-specific [56]. The lack of universal standards that specify the acceptable levels of heavy metals as a global template has led to debates and scientific discussions. Hence, a comparison of this study against the primary internationally accepted standards was necessary, where the heavy metal types that were tested correspond to parameters specified in the Qatari standards. The results of comparison in Table 6 show impressive results for the biosolids currently produced in Qatar, whose pollutant levels are well below the international minimum levels considered acceptable. The Qatari government has arranged for raw sewage sludge to be sourced from non-industrial and non-medical sources [25]. The mean for all sample parameters in Table 6 illustrates the superiority of the Qatar biosolids when compared with other similar products in terms of the low levels of heavy metals. This could be attributed to the sources of raw sludge, to the efficient production process and treatment method used, and to the stringent sludge management policies.

3.2. The Effect of Biosolids on Tomatoes

The measurement of plant characteristics, including for the stems, leaves, and fruits, was conducted to assess the effectiveness and efficiency of the different types of fertilizers and soil textures. The dry matter results indicated no significant differences in the lengths of the three parts, with $p = 0.57$ for the stem, 0.69 for the leaves, and 0.12 for the fruits. However, the results from the biosolid treatments indicated that they achieved substantial growth, as compared to when cow manure and peat moss were used. The treatment with 5 kg/m^2 biosolids resulted in a 14.06% gain in dry matter as compared to 13.86% for the control treatment with 5 kg/m^2 of manure and peat moss. Moreover, treatment with 7 kg/m^2 biosolids resulted in only a 11.81% gain in dry matter.

The dry matter of leaves (treated with 5 kg/m^2 of biosolids) ranked the highest at 14.42%, followed by the control treatment with 5 kg/m^2 of cow manure at 13.94% and then the 7 kg/m^2 biosolid treatment at 13.31%. Unlike the stem and leaf measurements, the dry matter percentage of the fruits was 5.59% for the 5 kg/m^2 biosolid treatment and 4.63% for the 7 kg/m^2 biosolid treatment. The results for the control treatment of 5 kg/m^2 manure and peat moss were 4.54%. Although there were statistically non-significant minor differences in dry matter among the treatments, they still indicated that biosolid treatments were rich enough to develop biomass equal to that obtained from cow manure and peat moss. Furthermore, the results, as highlighted in the Table 7, showed that the proper nutritional needs of tomato plants were met with both 5 kg/m^2 of biosolids and manure with peat moss, as compared to those plants treated with 7 kg/m^2 of either, given that plants vary in their fertilization requirements [30].

Table 6. Comparison of Heavy Metal Contents against International Standards.

			Sludge Quality Standards										
			Agriculture									Landscaping	
			USEPA (Part 503 Rule)	Qatar Biosolid	*GCC	Abu Dhabi	Bahrain		Australia and New Zealand	EC(86/278/EEC)			*QCS 2014
Parameters	Unit	Weighted Average Sludge Content (2009)	Exceptional Quality Limit	Mean of All Samples	Limit	Average as % of Limit Value	Unrestricted Use	Restricted Use	(Proposed)	*C1 Soil Contaminant if Ceiling Exceeded Ceiling Should Not Be Used	*C2 If Exceeded Should Not Be Used	Upper Limit	Maximum Concentration
Zn	mg/kg	801.0	2800	0.00	500	160%	300	2500	2800	200–250	2500	4000	200
Cu	mg/kg	591.0	1500	n.d.	400	148%	150	1000	1500	100–200	2500	1750	100
Ni	mg/kg	26.0	420	0.02	200	13%	60	300	420	60	270	400	60
Cd	mg/kg	0.9	39	0.2 n.d.	20	4%	1	20	39	11	20	40	1
Pb	mg/kg	24.3	300	0.016	300	8%	300	750	300	150–300	420	1200	150
Hg	mg/kg	1.5	17	n.d.	10	14%	1	10	17	1	15	25	1
Cr	mg/kg	32.0	/	0.04	300	11%	400	1000	1200	100–400	500–3000	/	100
As	mg/kg	2.7	18	0.003	10	26%	20	75	41	20	60	/	20
Se	mg/kg	1.6	36	n.d.	50	3%	3	50	36	3	50	/	5
Mo	mg/kg	9.2	41	n.d.	20	46%	20	75	/	/	/	/	/
Co	mg/kg	9.2		0.3 n.d.									
Mg	%	1.7		36.54									
pH		6.1		6.38									
EC	dS/m	3.5		3.43	10	35%							
OM	%	66.3		63.14	>35								
N	%	5.5		53.94									
N03-N	mg/kg	<0.1		6.13									
P	%	1.8		19.12									
K	%	0.4		3.14									

(RECYCLING) (EPA 1997) [57–62]. * GCC: The Gulf Cooperation Council. * QCS: Qatar construction specifications.* C1 and C2: Unified Guidebook of Building Permit Regulations 1 and 2.

Table 7. Averages and standard deviation of plant characteristics parameters for different treatments.

Treatments	Average of Plant Height (cm)	St. D ±	Average of Fruit Densities (pcs)	St. D ±	Average of Stem Diameter cm	St. D ±	Average of Leaves Length cm	St. D ±	Average of Leaves width cm	St. D ±	Average of Fruit Size Perimeter/cm	St. D ±
Control 5 kg cow manure and 20 L peat moss	114	±6	6	±2	7.22	±0.88	12.20	±0.33	5.66	±0.73	9.43	±1.15
7 kg Biosolids + Soil	116	±20	8	±2	6.72	±0.62	11.53	±0.66	5.16	±0.24	9.18	±0.22
5 kg Biosolids + Soil	106	±21	8	±1	7.07	±0.39	12.56	±0.66	5.70	±0.51	8.95	±0.86

Height is one of the main parameters that can be measured in plants to assess their growth rate [63]. This study measured the height of tomato plants to evaluate the efficiency of the examined organic fertilizers; plant yield and height are also indicators linked to other factors, such as lifespan and fruiting stages. The height of plants is correlated with their contents and levels of supplementary nutrients, both of which emphasize the importance of assessing plant growth. Our results showed no significant differences among treatments, with $p = 0.8$, confirming that the biosolid treatments, as sources of nutrients, can be considered equivalent to cow manure and peat moss, a conclusion which has also been reached in many other studies [64]. The quantitative link between the fruit density of tomatoes and the level of nutrients is also an essential relation, which has been indicated by many studies [65]. This relationship is determined by measuring the gained yield and comparing the fruit density among the different treatments in this study. The statistical analyses highlighted no significant differences among all treatments. With $p = 0.44$, it can be concluded that a similar number of fruits developed as a result of treatment with either biosolid treatments or regular manure and peat moss, which are used for standard production in Qatar.

The stem diameter in tomato plants is also a sensitive parameter that indicates growth. Although the water had been monitored and adjusted daily inside the greenhouse, as the irrigation system was centralized, the variations are attributed to the other correlated parameters such as nutrients and the water-holding capacity of the organic soil content. The results reflected no significant differences among treatments, with $p = 0.81$. It was clear that the stem girth in tomatoes significantly developed as a result of treatment with either biosolid or cow manure and peat moss, which could therefore be considered equal.

The plant leaf growth is another indicator used to assess the influence of the surrounding environment, which includes nutrients [66]. Unlike outdoor farming of tomatoes, growth within the controlled environment of the greenhouse minimizes interactions between factors and simplifies the assessment methodology. In this study, measurements of the plant leaf length and width were acquired to highlight the plant response to variable treatments and different soil contents. The statistical analysis of the results indicates no significant differences between treatments on the leaf length and width, with $p = 0.3$ and 0.13, respectively. It was another positive indicator concerning the efficiency of biosolids as organic fertilizer. Similar results were observed for both 5 and 7 kg/m^2 rates for the application of cow manure and peat moss.

The study measured the yielded fruit size perimeter/cm to comprehend the impact of applying different rates of biosolid as an organic fertilizer. Such a qualitative parameter has commonly been used to assess the growth and the levels of nutrients supplied during the growing season. The quality of the fruits, coupled with plant productivity, was crucial in vegetable and fruit production. Our statistical analyses revealed no significant differences among all treatments, with $p = 0.6$. This further illustrates the ability of the different biosolid application rates (i.e., 5 and 7 kg/m^2) to enhance the quality of the fruits, as compared to the enhancement gained by using 5 kg of cow manure plus 20 Ls of peat moss/m^2.

3.3. Chemical Analysis

To allow for a more holistic interpretation of the above results, chemical analysis of the treatments was carried out to complete the study. The total level of nitrogen present was investigated, since tomato plants cannot synthesize nitrogen, which will allow the role of biosolids as an organic fertilizer for tomatoes to be further assessed. Hence, tomato plants must acquire nitrogen from other sources, such as the soil and organic or agrochemical fertilizers [45]. The statistical interpretation of the results indicated non-significant differences in total nitrogen levels for the stems, leaves, and fruits, with $p = 0.28$, 0.93, and 0.09, respectively. The mean of all the treatments revealed that the highest level of total nitrogen in the stems was with the treatment of 7 kg/m^2 of biosolids with a mean of 18.72 mg/kg, followed by the treatment of 5 kg/m^2 of biosolids with 8.76 mg/m^2, and then the treatment of 5 kg/m^2 manure and 20 Ls/m^2 peat moss with an average of 8.23 mg/kg.

The nitrogen levels resulting from both rates of biosolid treatments was higher than that of the manure and peat moss treatment, and this could be attributed to the high nitrogen content of the biosolids [24]. The treatment of 7 kg/m^2 biosolids also showed the highest levels of nitrogen in the leaves at 19.53 mg/kg but, in this case, was followed by the control treatment with a mean of 19.11 mg/kg, and then the treatment of 5 kg/m^2 biosolids with a mean of 14.84 mg/kg, with slight differences between the other treatments. For the fruits, the leading mean was the control treatment with a mean of 11.65 mg/kg, followed by the treatment of 7 kg/m^2 biosolids at 3.72 mg/kg, and then the treatment of 5 kg/m^2 biosolids at 3.27 mg/kg of total nitrogen. This could be attributed to the formulation of biosolids as pellets, which were designed to ensure a slow release of nutrients and therefore require longer periods to function—which is precisely the way in which other organic matter releases nutrients.

Boron is one of the leading microchemical elements required by plants. Although only trace amounts are needed, it plays a pivotal role in plant lifecycles [67]. The statistical results showed non-significant differences in all treatments with a $p = 0.56$ for stems, 0.35 for leaves, and 0.1 for fruits. Moreover, interpreting the mean figures sheds more light on these results, as it suggests that the highest presence of boron was at the stems in the 5 kg/m^2 biosolid treatment group with 50.43 mg/kg, followed by the manure and peat moss treatment group with 44.57 mg/kg, and the lowest concentration was for the 7 kg/m^2 biosolid treatment group with 44.18 mg/kg. Similarly, the results in the leaves mirrored those results with the same with a sequence of treatments at 189.98, 123.89, and 90.72 mg/kg, respectively.

By contrast, for the fruits, the 5 kg/m^2 biosolid gained 43.7 mg/kg of boron, followed by the 7th kg/m^2 of biosolids with a presence of 36.42 mg/kg, and the lowest was found in the manure and peat moss treatment with a level of 22.12 mg/kg. The differences were statistically non-significant. However, depending on the overall plant growth in these treatments, both biosolid treatments were comparable to the control treatment as a good source of boron, as they had resulted in plants with similar growth to the controls and without any signs or symptoms of boron deficiency.

For calcium (Ca), the statistical analysis revealed no significant differences among treatments in all investigated parts at $p = 0.86$ for the stems, 0.65 for the leaves, and 0.54 for the fruits. The importance of this microelement and the need to further understand the results encouraged us to examine the means of calcium present in all plant parts. The results showed a higher presence of calcium in biosolid treatments for all parts. By contrast, the treatment with 7 kg/m^2 of biosolids showed levels of Ca were 82.31 mg/kg in the stems, followed by the treatment with 5 kg/m^2 biosolids with 81.39 mg/kg for Ca. The control treatment had a mean value of 75.84 mg/kg. Only the sequence of treatments showed much variation, with 5 kg/m^2 biosolids resulting in 230.57 mg/kg, 7 kg/m^2 biosolids resulting in 133.58 mg/kg, and the control treatment resulting in 123.22 mg/kg. Subsequently, the mean levels of calcium in the fruits reflected the same sequence with 48.84 mg/kg for the 5 kg/m^2 biosolids and 23.92 mg/kg for the 7 kg/m^2 biosolids, followed by the control treatment with 5.26 mg/kg. These results are feasible as the biosolids used have been recognized for their high content of minerals, and there were no signs that the soil had biosolid additives. These important microelements performed better under experimental conditions than under the control conditions.

Copper (Cu) is another microelement that is required by plants in trace amounts. The role of copper can be summarized as being an important contributor in carbohydrate and chlorophyll synthesis and being a critical factor in metabolic processes involving nitrogen [68]. The results revealed no significant differences among treatments in the stems and fruits of plants, with $p = 0.81$ and 0.24, respectively. Unlike the stems and fruits, the results for the leaves indicated significant differences among treatments with $p = 0.05$. The mean figures for the copper content in leaves were as follows: 602.04 mg/kg with the treatment of 5 kg/m^2 biosolids; 339.9 mg/kg with the treatment of 7 kg/m^2 of biosolids; and, finally, 306.6 mg/kg with the control treatment. These results can be explained by the high heavy metal content in the biosolids as compared to other organic matters, and based on the nature of its origin, which has been acknowledged in many studies [69]. Hence, it was essential to compare the levels of pollutants and nutrients with the internationally acceptable levels of the same minerals in tomatoes to assess the biosolid's actual effects and develop a conclusion.

The utilization of magnesium by plants can be affected by other minerals, such as potassium or calcium, being present at high levels, which makes it more challenging to diagnose the symptoms of deficiency and pushes farmers to do whatever they can to ensure its continuous supply via chemical fertilizers [70]. The results highlighted no significant differences in magnesium levels among all treatments, with $p = 0.75$ for the stems, 0.74 for the leaves, and 0.28 for the fruits. The results are in accordance with the overall condition of the plants, with no clear evidence of magnesium deficiency identified throughout the continuous monitoring of the plants during the study period. Similarly, the results show that both biosolid treatments performed adequately, as compared to regular organic manure and peat moss, which are good sources of magnesium. To support this conclusion, the magnesium levels were measured in each part of the plants under all treatment conditions. For the stems, the highest rate of magnesium, 21.36 mg/kg, was recorded in plants subject to 5 kg/m^2 biosolid treatment, followed by 19.82 mg/kg for the control treatment and then 18.69 mg/kg for treatment with 7 kg/m^2 of biosolids. The same sequence was observed in leaves, with the presence of 20.23, 12.63, and 12.56 mg/kg, respectively. For the fruits, it was noticeable that both biosolid treatments showed a higher presence of magnesium with 8.93 mg/kg for the 5 kg/m^2 treatment and 8.84 mg/kg for the 7 kg/m^2. Lastly, the control treatment of manure and peat moss was the lowest with 4.38 mg/kg, which was also observed in the condition and shape of fruits. Generally, the overall yield of the two experimental treatments appeared higher as compared to the control treatment.

Manganese (Mn) is another micronutrient needed for tomato production. It also is required in trace amounts, but it is essential to measure it due to its central role in cell function and being a key element in chlorophyll synthesis, in addition to its role in forming ascorbic acid, commonly known as vitamin C [71]. The results varied for this mineral, revealing non-significant differences among treatments for the stems and fruits with $p = 0.45$ for the stems and 0.86 for the fruits. Subsequently, the leaf statistical analysis showed significant differences among treatments, with $p = 0.01$. The results highlight that the differences were mainly between the control treatment, with a mean of 153.86 mg/kg, and treatment with 7 kg/m^2 biosolids, with a mean of 56.85 mg/kg. On the other hand, the treatment of 5 kg/m^2 biosolids had a mean of 103.94 mg/kg. It was expected that variations would be found in the leaves as they are a hotspot for chlorophyll synthesis, where Mn has the most significant impact. Our results did not suggest any Mn deficiency in the plants, and the differences were detected only in leaves. Furthermore, the presence of Mn in the stems and the fruits did not reflect any significant differences for these parameters and still showed that the biosolids fulfilled the plants' needs.

Phosphorus (P) plays a crucial role in plant growth, being a significant component in nucleic acid and its multiple roles in increasing fruit quantity and quality and being a key element in transferring energy. Furthermore, it is the main factor involved in total soluble solids and flowering in tomatoes [72]. The statistical analyses of the randomized complete block design method revealed no significant differences among all treatments, with $p = 0.59$ for the stems, 0.53 for the leaves, and 0.35 for the fruits. These results were expected as organic matter, in general, and particularly the biosolids assessed in this study, are rich in macro-elements [73]. It was therefore crucial to look at the recorded levels of phosphorus to draw an informed conclusion. The biosolid treatments showed higher phosphorus contents, with $p = 12.89$ mg/kg in the stems with 5 kg/m^2 biosolids, 10.78 mg/kg for 7 kg/m^2 biosolids, and 6.38 mg/kg for the control treatment. The same sequence was observed in the leaves with 22.91 mg/kg with the 5 kg/m^2 biosolid treatment, followed by 16.56 mg/kg for the 7 kg/m^2 biosolid treatment, and 11.47 mg/kg for the control treatment. A slight change was recorded for the fruits as the 7 kg/m^2 treatment resulted in

27.15 mg/kg, followed by the 5 kg/m^2 biosolid at 23.49 mg/kg, and the lowest was for the control treatment at 16.56 mg/kg. The interpretation of the results showed that both biosolid treatments outperformed the control treatment in terms of phosphorus contents, though the differences were not found to be statistically significant.

The levels of potassium, unlike those of other elements, tend to be high in alkaline soils, such as those found in Qatar [74]. This element is involved in many key functions in tomato plants, such as in preserving water and balancing ions [75]. Furthermore, it is involved in the regulation of numerous processes linked to the formation of proteins and enzymes, sugar distribution, and synthesis [76]. Studies have highlighted this element's crucial role in producing high-quality fruit by controlling the percentages of sugars and influencing ripening [77]. The results reflected no significant differences among all treatments, with $p = 0.4$ for the stems, 0.73 for the leaves, and 0.23 for the fruits. The relative similarity was not a barrier to investigating the actual treatment means to understand these results further. The potassium levels in the stems recorded among the treatments indicated that both biosolid treatments of 5 and 7 kg/m^2, with levels of 117.2 and 86.7 mg/kg, respectively, outperformed the control treatment with 54.2 mg/kg. For the leaves, 120.2 mg/kg was measured for the 5 kg/m^2 biosolid treatment, 67.4 mg/kg for the control treatment and, finally, 54.6 mg/kg for treatment with 7 kg/m^2 biosolids. For the fruits, the 7 kg/m^2 biosolid treatment showed the highest potassium levels at 214.5 mg/kg, followed by the other biosolid treatment of 5 kg/m^2 at 147 mg/kg and, lastly, the control treatment at 129.5 mg/kg. These different sequences could not be considered as variations since the statistical analyses revealed no significant differences. However, these results confirmed that the overall conditions for tomato plants were met when they were fertilized with biosolids. The experimental treatments show the possibility of the standard organic manure being superseded as the organic fertilizer of choice.

As shown in Table 8 and similar in importance to Mn and Mg, zinc (Zn) is involved in enzymatic functions to promote and regulate growth. It participates in chlorophyll synthesis and is needed by plants in trace amounts [41]. The statistical results showed no significant differences among different treatments, with $p = 0.2$ for the stems and 0.6 for both the leaves and the fruits. An investigation of the level of zinc among treatments in each part revealed the highest presence in stem, which was found at 297.4 mg/kg in the control treatment, followed by the biosolid treatments, with 295.7 for 5 kg/m^2 and 209.8 mg/kg for 7 kg/m^2. In the leaves, the biosolid treatments were higher than the control treatment, with 195.8 mg/kg for 5 kg/m^2 biosolids and 175.01 mg/kg for 7 kg/m^2 biosolids, while 127.6 mg/kg was found for the control treatment. Zn was higher in the fruits under both experimental treatments of 5 and 7 kg/m^2, at 137.8 and 112.7 mg/kg, respectively, as compared to the control treatment at 108.26 mg/kg. Statistically significant differences across all parts and all treatments of the tomato plants might have provided incontrovertible evidence to support the use of biosolids as a suitable substitute for standard fertilizer. Nevertheless, our overall results support the use of biosolids as organic fertilizer. It is, however, still crucial that our recorded levels in tomato plants fertilized with biosolids produced in Qatar be compared to the international standards for acceptable levels of each element (Table 9; Figure 1).

Table 8. Elemental composition of tomatoes grown on biosolids.

Treatment	Tot. N	St. D.	B	St. D.	Ca	St. D.	Cu	St. D.	Mg	St. D.	Mn	St. D.	P	St. D.	K	St. D.	Zn	St. D.
Control 5 kg/m^2 Manure and 20 L/m^2 Peat Moss	11.65	±5.05	22.12	±8.32	5.26	±1.56	159.21	±92.5	4.38	±2.26	53.18	±30.1	16.56	±6.4	129.54	±71.4	108.3	±39.7
5 kg/m^2 Biosolid	3.27	±0.75	43.7	±10.78	48.84	±69.30	274.13	±143.4	8.93	±4	53.77	±21	23.49	±13.9	147	±90	137.8	±35.1
7 kg/m^2 Biosolid	3.72	±2.38	36.42	±18.09	23.92	±23.58	260.27	±98.8	8.84	±2.3	43.32	±21.8	27.15	±4.2	214.53	±35.3	112.7	±47.8

3.4. Comprehensive Analysis

Investigating tomato fruits' growth and nutrient parameters revealed many relevant points that may help to counter social resistance to the usage of biosolids as an organic fertilizer for edible fruits and vegetables. Most of the parameters that are tested in fertilized fruits, including tomatoes, represent major nutrients. However, these fruits can become toxic if high levels of these nutrients are accumulated can be toxic [77]. As shown in Table 3 and line graph 2, both the world health organization WHO and the food and agricultural FAO as highlighted in Table 9 and Figure 1 have defined restrictions for most of these parameters in tomato fruits, including for heavy metals such as zinc, copper, and manganese. However, the same organizations have not specified the maximum presence or acceptable levels for many other nutrients, including nitrogen, phosphorus, and potassium [78]. The lack of specificity may be a result of difficulties in determining the exact levels and accounting for global variability and diverse conditions that impact the toxicity mobility, and quality of such nutrients, all of which may diminish their importance in influencing plant productivity, growth, and yields [77]. When examining the macroelements N, P, and K, it is evident that these nutrients are present at high levels in plants treated with biosolids compared with the control. Their presence in the fruits, as measured in our study, indicated that the experimental biosolid treatments were more effective than the control treatment for providing these nutrients, though their toxicity parameters in tomato plants were not examined. However, the maximum acceptable levels of certain heavy metals, as defined by international health organizations, that can be found in tomatoes present certain challenges. For example, the highest acceptable level of zinc is 1.5 mg/kg. Under treatment conditions of 5 kg/m^2 biosolids, we recorded a Zn level of 137.82 mg/kg, and with 7 kg/m^2 biosolids, 112.71 mg/kg, which vastly exceed the acceptable level.

Similarly, the maximum acceptable level of copper is 2.00 mg/kg, and the 5 kg/m^2 biosolid treatment showed a copper level of 274.13 mg/kg while the 7 kg/m^2 biosolid treatment showed 260.72 mg/kg. Furthermore, the maximum acceptable level of manganese is 5.0 mg/kg. In our study, the 5 kg/m^2 biosolid treatment resulted in an Mn level of 53.77 mg/kg and 43.32 mg/kg for the 7 kg/m^2. These significant differences between the acceptable international levels and the levels discovered in tomato fruits fertilized with biosolids highlight the unsuitability of biosolids produced in Qatar for fertilizing plants from which edible fruit is collected. These toxic chemical compounds can accumulate in the human body and contribute significantly to the development of numerous diseases such as cancer [79]. The application of biosolids successfully promoted plant growth equally to or better than regular manure. However, the physiological and productivity enhancements cannot compensate for the results indicating the toxicity of fruits due to the presence of heavy metals. Therefore, these results may support the use of biosolids as organic fertilizer for inedible, ornamental plants, though the potential for such and application would require further research. In terms of using biosolids as an organic fertilizer for edible plants, future research should include a survey of experiments completed in other countries worldwide and examine their outcomes.

Table 9. Comparison between the discovered concentrations of pollutants and the acceptable levels according to WHO/FAO.

Pollutants	Levels of Tested Parameters of Biosolids		WHO/FAO Maximum Acceptable Levels in Tomatoes mg/kg
	5 kg Biosolids	7 kg Biosolids	
Zinc (Zn) mg/kg	137.82	112.71	1.5
Cupper (Cu) mg/kg	274.13	260.72	2.00
Manganese (Mn) mg/kg	53.77	43.32	5.00

References [80,81].

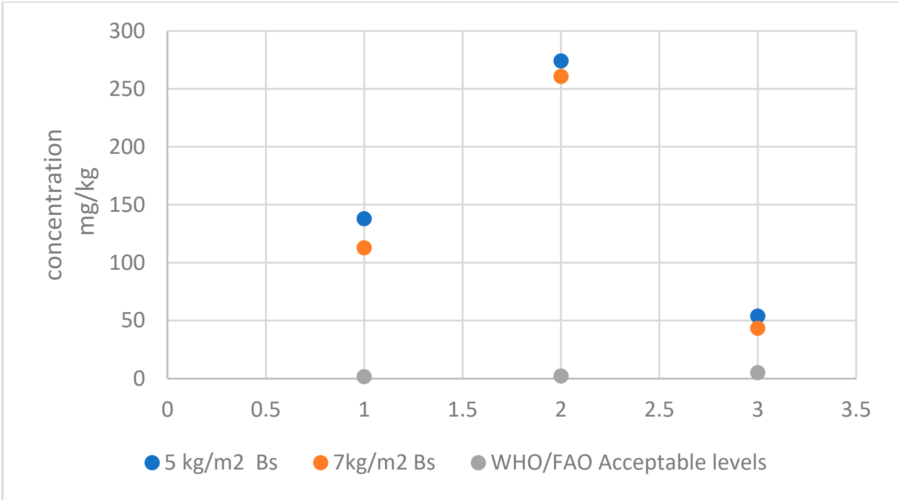

Figure 1. Differences between the discovered concentrations of pollutants and the acceptable levels according to WHO/FAO.

4. Conclusions

In this study, Qatar's class A biosolids were comprehensively analyzed and described. The sampling was based on specific time intervals of three months between each sample. The biosolid's temporal characteristics (chemical and physical) had very promising results in terms of stability, with slight variations recorded among the samples. The physical analyses highlighted that the pellet formation complied with the specified pellet sizes, with some deficiencies in odor treatment, which was considered a minor defect. Furthermore, the chemical analysis of parameters such as pH, electrical conductivity, and organic matter content, among others, either complied with the local, regional, and international standards or fell below the required levels. Investigations concerning the levels of nutrients, such as nitrogen and phosphorus, illustrated the richness of the treatment and its suitability for use as an organic fertilizer or soil amendment. In addition, the levels of heavy metals as the main pollutant indicated a value well below international levels. Spectrometry did not reveal the absence of detectable levels of several major toxic heavy metals (e.g., mercury, cobalt, and cadmium). The levels of the remaining heavy metals were lower than the US EPA standards, thus demonstrating the exceptional quality of the sludge. Based on these results, biosolids appear benign for use as an organic fertilizer and soil amender in landscaping projects. This is attributed to the processing technology using the Swiss Combi treatment method. The DNSTP was designed as an efficient technology to manage biosolids' physical properties and dryness and the particle size of pellets and their levels of pollutants and nutrients. Furthermore, the interpretation of the results from using biosolids as organic fertilizer for tomato production reflected extraordinary growth and development of the plants (*Solanum lycopersicum*). The pots were fertilized with two different rates of biosolids, 5 and 7 kg/m^2, with no substantial variances in the results as compared to the control treatment with 5 kg/m^2 of cow manure and 20 Ls/m^2 of peat moss. Most of the plant characteristics revealed non-significant differences between the examined rates of biosolids versus manure in the stems, leaves, and fruits. However, the chemical analysis of the fruits indicated high concentrations of heavy metals that were significantly higher than the highest acceptable levels for human consumption as specified by global health organizations, including the World Health Organization (WHO) and the Food and Agriculture Organizations (FAO) of the United Nations. Our results highlighted the efficiency of biosolids as an organic fertilizer. Our analysis of the plant characteristics as a result of the three treatments revealed that there was no significant difference in plant height, fruit density, stem girth, leaf length and width, and fruit size perimeter. Nevertheless, there was a significant difference in the analysis of the dry matter for all three treatments. The chemical analysis of the three treatments provides important information that should be considered when making informed decisions. There were no significant differences in total nitrogen, boron, calcium, magnesium, manganese, phosphorus, and potassium under all treatment conditions. On the other hand, there were significant differences between copper and zinc. We confirmed that the main challenge involved in the use of biosolids as organic fertilizer in the production of edible fruits, namely tomatoes, was the trace amounts of heavy metals that exceeded acceptable limits, resulting in fruits that are hazardous for human consumption. For instance, the excessive accumulation of trace heavy metals, such as zinc, manganese, and copper, was found in the tomato fruits, which would make them toxic for humans. This confirmed that the Qatari biosolids are unsuitable for use as an organic fertilizer in agricultural practices. Unless significant advancements in treatment methodology or sewage processing are developed to mitigate the presence of heavy metals in sewage byproducts such as biosolids, the potential of human excreta treated at the Doha North Sewerage Station Plant to be used as organic fertilizer for edible plants in Qatar will remain unrealized.

Author Contributions: Conceptualization, T.A.; methodology, M.A.; data curation, M.A.; writing—original draft preparation, M.A.; writing—review and editing, T.A., M.A.-G. and M.A.-D.; supervision, T.A. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by Qatar University Student Grant, grant number QUST-1-ESC-2019-2. The statements made herein are solely the responsibility of the author(s).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

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

Ethical Statement: The research is ethically compliant, and no animals were involved in this research.

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