

Article

Integrated National Assessment of Biosolids Reuse for Sustainable Agriculture in Jordan: Soil Fertility, Land Suitability, and Environmental Considerations

Nisreen Obeidat ^{1,*} , Amer Sweity ^{2,*}, Ahmad Abu Awwad ¹ , Rima S. Taha ³, Jaffar Y. M. AlKassasbeh ², Nabeel Bani Hani ², Sarah Jaradat ⁴ , Moroug Zyadeh ⁵ , Rima Heider Al Omari ⁶  and Ola A. Da'na ⁷ 

¹ Department of Land, Water and Environment, The University of Jordan, Amman 11942, Jordan

² Water and Soil Research Directorate, National Agricultural Research Center (NARC), Baqa'a 19381, Jordan

³ Department of Allied Medical Sciences, Zarqa University College, Al-Balqa Applied University, Al-Salt 19117, Jordan

⁴ Department of Nutrition and Food Technology, The University of Jordan, Amman 11942, Jordan

⁵ Department of Plant Production-Smart and Sustainable Agriculture, Ajloun National University, Ajloun 26810, Jordan

⁶ Medical Laboratory Sciences Department, Al-Ahliyya Amman University, Amman 19111, Jordan

⁷ Department of Nutrition and Integrative Health, Middle East University, Amman 11831, Jordan

* Correspondence: n.alobeidat@ju.edu.jo (N.O.); amer.sweity@narc.gov.jo (A.S.)

Abstract

This secondary-data integrated assessment combines national wastewater treatment records, two national sludge reports, Jordanian regulatory criteria, published agronomic evidence, engineering scenarios, and a previously prepared spatial screen. The present national context includes 33 municipal wastewater treatment plants (WWTPs), but the analytical sources cover different historical plant sets. The 2020 GIZ report surveyed 29 operating WWTPs and reported sludge-quality data for 25 plants, comprising 28 plant-stage records. The 2014 USAID strategy covered 28 WWTPs, with metal data for 9 plants and six nutrient samples from 3 plants. In the GIZ records, mean concentrations were 3.44 mg Cd kg^{−1}, 7.93 mg Pb kg^{−1}, 603.79 mg Zn kg^{−1}, and 111.86 mg Cu kg^{−1} dry solids. Maximum concentration-to-limit ratios were 1.00 for Cd, 0.103 for Pb, 0.525 for Zn, and 0.377 for Cu. USAID nutrient samples averaged 3.93% total N, 1.71% total P, and 0.71% total K. GIZ estimated 101,533–108,719 t dry solids yr^{−1} in 2020 and 128,540–149,332 t yr^{−1} in 2035. USAID produced lower estimates of 50,947 and 72,418 t yr^{−1} for the same years, showing major model uncertainty. The source spatial screen mapped 10,150.28 km², including 745.62 km² of protected rangeland reserves. Excluding those reserves leaves 9404.66 km² for further regulatory and field screening. The results support controlled reuse based on batch testing, pathogen reduction, nitrogen and phosphorus budgets, and long-term soil monitoring.

Keywords: biosolids reuse; nutrient mineralization kinetics; phosphorus dynamics; sewage sludge valorization; soil organic matter; sustainable fertilization



Academic Editor: Claudio Ciavatta

Received: 21 August 2026

Revised: 6 September 2026

Accepted: 19 September 2026

Published: 30 September 2026

Copyright: © 2026 by the authors.

Licensee MDPI, Basel, Switzerland.

This article is an open access article distributed under the terms and conditions of the [Creative Commons Attribution \(CC BY\)](https://creativecommons.org/licenses/by/4.0/) license.

1. Introduction

The increasing generation of sewage sludge as a by-product of municipal wastewater treatment has become a major environmental and resource management challenge worldwide. The continuous expansion of wastewater treatment infrastructure, stricter environmental regulations, and improved treatment efficiencies have substantially increased

sludge production over recent decades [1,2]. Conventional disposal practices, including landfilling, incineration, and uncontrolled land application, are becoming increasingly unsustainable because of their environmental impacts, rising operational costs, and the loss of potentially valuable resources [3]. Consequently, wastewater management strategies are progressively shifting from waste disposal toward resource recovery and circular economy approaches, in which sewage sludge is considered a renewable source of organic matter, nutrients, and energy rather than a waste requiring disposal [4–6].

Following appropriate stabilization and treatment, sewage sludge can be converted into biosolids that provide significant agronomic benefits when applied to agricultural soils. Biosolids contain considerable amounts of organic matter together with essential plant nutrients, particularly nitrogen (N), phosphorus (P), and potassium (K), making them an attractive alternative or supplement to mineral fertilizers [7–9]. Unlike synthetic fertilizers, biosolids supply nutrients through both immediately available and slow-release forms, thereby improving nutrient use efficiency while enhancing soil organic matter, cation exchange capacity, soil aggregation, microbial activity, and water-holding capacity [10–12]. Recent advances in soil microbiome research have further demonstrated that organic amendments such as biosolids can stimulate beneficial microbial communities, enhance rhizosphere processes, improve nutrient cycling, and increase soil resilience to environmental stresses, thereby contributing to sustainable agricultural production [13,14]. These characteristics are particularly beneficial for degraded and nutrient-deficient soils, where organic amendments improve soil structure, biological activity, and long-term soil fertility [11,12].

Despite these advantages, the agricultural reuse of biosolids remains constrained by environmental, agronomic, and public health considerations. Potential accumulation of heavy metals, persistence of pathogenic microorganisms, and increasing concern regarding emerging contaminants—including pharmaceuticals, endocrine-disrupting compounds, antibiotic resistance genes, per- and polyfluoroalkyl substances (PFAS), and microplastics—require careful evaluation before widespread agricultural application [13–15]. The environmental behavior of these contaminants depends on complex physical, chemical, and biological processes, including adsorption, precipitation, degradation, transport, and bioavailability, all of which are strongly influenced by soil characteristics, climatic conditions, and biosolids properties [15–20]. Consequently, sustainable biosolids management requires not only compliance with regulatory standards but also a comprehensive understanding of nutrient dynamics, contaminant behavior, and long-term environmental impacts.

These considerations are particularly important in arid and semi-arid regions, where improving soil quality and water-use efficiency are fundamental to sustainable agricultural production. Jordan is among the most water-scarce countries in the world, with more than 90% of its territory classified as arid or semi-arid and annual rainfall below 200 mm across most of the country [21]. Agricultural soils are generally characterized by low organic matter content, weak structural stability, and limited nutrient availability, while increasing climate variability and prolonged drought conditions continue to threaten agricultural productivity [22]. Recent studies have highlighted the importance of integrated soil management and drought-resilient agricultural systems to improve crop performance under increasingly water-limited environments [23]. Under these conditions, biosolids represent a potentially valuable soil amendment capable of improving soil fertility, increasing water retention, enhancing nutrient availability, and reducing dependence on mineral fertilizers [24–30]. Several studies conducted in Jordan have reported improvements in soil physical properties, nutrient availability, and crop productivity following biosolids application under different cropping systems and environmental conditions. However, these investigations have generally focused on individual crops, specific field experiments,

or localized conditions, providing limited information for national-scale planning and decision-making [31–40].

At the same time, the continued expansion of Jordan’s wastewater treatment infrastructure has resulted in steadily increasing biosolids production, creating both an environmental management challenge and an opportunity for resource recovery [41]. Although previous studies have investigated individual aspects of biosolids reuse—including sludge characterization, crop response, nutrient availability, and environmental quality—few have integrated engineering, agronomic, environmental, and spatial perspectives into a comprehensive national assessment. Furthermore, previous investigations have rarely combined sludge generation estimates, physicochemical characteristics, nutrient transformation processes, land suitability evaluation, and environmental risk considerations within a single analytical framework capable of supporting sustainable biosolids management under Jordanian conditions. This lack of an integrated assessment limits evidence-based decision-making for policymakers and resource managers seeking to promote the safe and sustainable reuse of biosolids within circular economy strategies.

This study presents a national secondary-data assessment of agricultural biosolids reuse in Jordan. The objectives were to compare published sludge-generation scenarios, summarize available physicochemical measurements, calculate transparent metal concentration-to-limit ratios, test nutrient-application scenarios, examine a previously prepared land-screening product, and identify evidence gaps affecting safe reuse. The study does not claim a complete 33-plant analytical dataset, a newly executed GIS model, or field validation.

2. Materials and Methods

2.1. Study Design

This study used a secondary-data integrated-assessment design. It did not generate new laboratory or field measurements. The analysis combined national WWTP inventory records, published physicochemical and microbiological measurements, Jordanian regulatory criteria, engineering calculations, and existing spatial products. The study evaluated biosolids generation, composition, nutrient availability, land-screening potential, and environmental risks under Jordanian conditions.

The methodological framework consisted of five sequential components: (i) assessment of current and future biosolids generation from municipal wastewater treatment systems; (ii) synthesis of physicochemical and microbiological characteristics of Jordanian biosolids; (iii) evaluation of nutrient-based biosolids application rates; (iv) spatial assessment of land suitability for agricultural reuse; and (v) evaluation of environmental risks associated with long-term biosolids application.

2.2. Literature Search Strategy and Data Sources

A targeted evidence search was last updated on 31 August 2026. Web of Science, Scopus, ScienceDirect, and Google Scholar were searched using the database-adapted string: (biosolid* OR “sewage sludge” OR “wastewater sludge”) AND (Jordan OR arid OR semi-arid) AND (agricultur* OR soil OR crop OR land application OR nutrient* OR metal* OR pathogen* OR GIS OR “land suitability”). A second search combined (Jordan AND wastewater treatment plant*) with (sludge production OR biosolids generation). Searches were not restricted by year because relevant Jordanian studies date from 1990 onward and source updates extend through 2026. Titles and abstracts were screened for direct relevance. Full texts were retained when they reported a Jordanian dataset, a national planning scenario, an applicable method, or evidence needed to interpret nutrient, contaminant, or soil processes. Duplicate records, conference abstracts without full methods, and

documents unrelated to agricultural sludge reuse were excluded. This targeted synthesis was not registered as a systematic review, so PRISMA-style database record counts were not reconstructed. Supplementary Table S1 provides the source-to-output audit trail, and Tables S2–S6 contain transcribed values and calculations.

The national infrastructure context used in this assessment listed 33 municipal WWTPs. This number describes the national system, not a matched set of 33 sludge samples. Quantitative sludge characterization relied on two earlier national reports. The GIZ sludge-mapping study conducted field visits at 29 operational WWTPs and presented plant-specific sludge-quality tables for 25 plants. Three plants contained measurements for two sludge stages, resulting in 28 stage-specific GIZ sample records. The USAID Kingdom-Wide Biosolids Management Strategy covered 28 WWTPs. The analytical coverage therefore differs by source, plant, sludge stage, year, and parameter.

The assessment used the 2020 GIZ Sludge Mapping in Jordan report, the 2014 USAID Kingdom-Wide Biosolids Management Strategy, Jordanian Standard JS 1145/2016 as reproduced in the national reports, published Jordanian studies, the Jordan National Master Plan, and cited soil and land-suitability sources [22,42]. GIZ metal concentrations reported in mg g^{-1} were converted to mg kg^{-1} dry solids by multiplying by 1000. Values preceded by a less-than sign were retained as censored records and excluded from arithmetic means and standard deviations. Values printed as 0.000 were retained as reported because record-specific detection limits were unavailable. Missing values were not imputed. Supplementary Table S2 preserves the reported strings and the converted numeric fields.

The system boundary encompassed sludge generation at municipal wastewater treatment plants, biosolids characterization, nutrient assessment, land suitability evaluation, and potential agricultural reuse pathways. Economic analysis was intentionally excluded to maintain emphasis on the technical, environmental, and agronomic dimensions of biosolids management, as shown in Tables 1 and 2 and Figure 1.

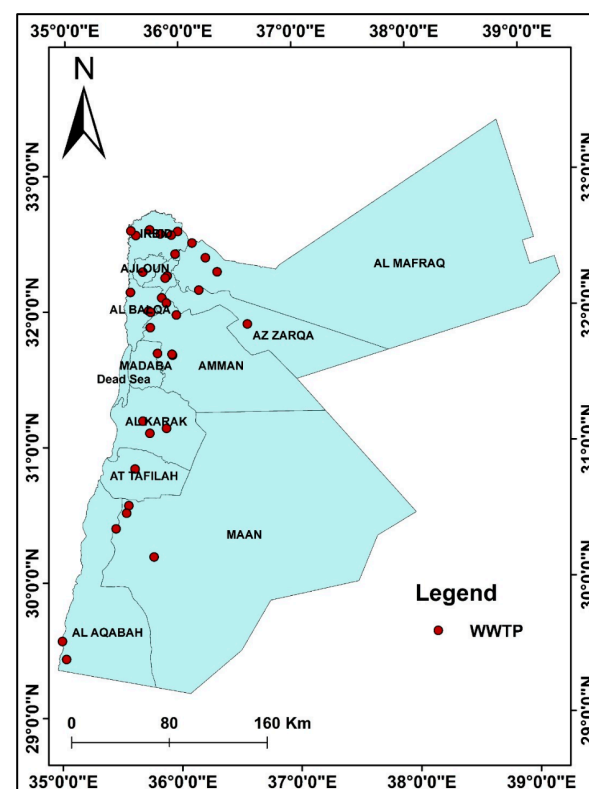


Figure 1. Geographic location of wastewater treatment plants (WWTPs) in Jordan.

Table 1. (a). Summary of wastewater treatment plants and sludge processing characteristics in Jordan. (b). Source-to-output audit trail.

(a)				
Dataset Scope	Plant Coverage	Analytical Coverage	Main Variables	Interpretation
Current national infrastructure context	33 WWTPs	Not a matched chemical dataset	Treatment and sludge-management context	System coverage only
GIZ sludge mapping	29 WWTPs visited	25 plants, 28 stage-specific records	Metals, pathogens, organic carbon, selected TN	Primary quantitative metal dataset
USAID national strategy	28 WWTPs covered	9 plants for metals; 3 plants $\times$ 2 nutrient samples	Cd, Pb, Zn, Cu, moisture, N, P, K, TVS	Historical supporting dataset
(b)				
Output	Exact Source		Processing	
WWTP coverage and treatment context	GIZ and USAID		Compiled; scopes kept separate	
Sludge-generation scenarios	GIZ and USAID		USAID kg d ^{−1} summed and multiplied by 365/1000	
Metals and pathogen class	GIZ		mg g ^{−1} multiplied by 1000; censored values excluded	
N, P, K, moisture, TVS	USAID		Six grab samples; no missing-value imputation	
Spatial-screen output	Source GIS map and area table; national planning sources		Arithmetic corrected; reserves separated	
Agronomic effects	Jordanian field and pot studies		Narrative synthesis; unsupported universal percentages removed	

Note: Full record-level values, formulas, and source locations appear in Supplementary Tables S1–S6.

Table 2. Classification criteria for biosolids quality based on JS 1145/2016.

Parameter	Type I/Class A Criterion	Type II/Class B Interpretation	Source and Use
Fecal coliform	≤ 1000 MPN g ^{−1} DS	Restricted use when Class A pathogen criteria are not met	GIZ amd JS 1145/2016
Salmonella	≤ 3 MPN per 4 g DS	Restricted use when Class A pathogen criteria are not met	GIZ amd JS 1145/2016
Helminth eggs	< 1 egg per 4 g DS	Restricted use when Class A pathogen criteria are not met	GIZ amd JS 1145/2016
Enteric viruses	< 1 PFU per 4 g DS	Restricted use when Class A pathogen criteria are not met	GIZ amd JS 1145/2016
Cd; Pb; Zn; Cu	40; 300; 2800; 1500 mg kg ^{−1} DS	Same listed metal ceilings; use remains subject to pathogen class and restrictions	GIZ amd JS 1145/2016

2.3. Study Area and Agro-Environmental Context

Jordan is characterized by predominantly arid and semi-arid climatic conditions, with more than 90% of the country receiving less than 200 mm of annual rainfall. Agricultural soils are generally characterized by low organic matter content, alkaline pH, and limited

nutrient availability, making organic amendments particularly important for improving soil fertility and water-holding capacity [7,26].

The assessment covered the major agro-ecological zones (AEZs) of Jordan, including the Highlands, Jordan Valley, Steppe, and Badia regions, which differ considerably in climate, soil characteristics, rainfall distribution, agricultural systems, and land use. These contrasting conditions provide an appropriate basis for evaluating the suitability of biosolids reuse under diverse environmental settings.

2.4. Data Processing and Integrated Assessment Framework

Information extracted from the different sources was organized into five thematic categories:

1. Biosolids generation;
2. Physicochemical characteristics;
3. Nutrient composition and agronomic value;
4. Land suitability;
5. Environmental risks.

Comparable measurements were summarized by source and parameter. For the GIZ heavy-metal records, the study calculated the number of exact numeric observations, arithmetic mean, sample standard deviation, minimum, and maximum. Censored observations were excluded from these calculations. USAID nutrient statistics were calculated from the six individual grab-sample results reported in Tables 3–7, except total volatile solids, for which five values were available. Aggregate organic-matter values from USAID Table 4–4 were reported separately because they were not assigned to individual plants. Plant-specific pH values were unavailable in the extracted quality tables. The analysis therefore avoids a false 33-plant mean for variables without matched observations.

Engineering equations describing sludge production, nitrogen mineralization, phosphorus dynamics, and environmental risk indicators were used to interpret published datasets rather than to generate independent experimental results.

2.5. Biosolids Characterization and Classification

Biosolids quality was evaluated from source-specific measurements of total nitrogen, total phosphorus, total potassium, organic matter, organic carbon, moisture, total volatile solids, heavy metals, and pathogen indicators. The GIZ dataset supported descriptive statistics for Cd, Pb, Zn, and Cu. The USAID sampling program supported descriptive statistics for moisture, N, P, K, and total volatile solids. Organic matter was available only as an aggregate range of 51.35–74.45%, with a reported average of 66%. Plant-specific pH data were not available. Table 3 report the quantitative evidence and the number of observations used for each statistic.

Table 3. Typical nutrient composition ranges of biosolids used in analysis.

Parameter	Unit	Range	Form	Role in Soil
Total Nitrogen (N)	%	2–5	Organic + NH_4^+	Slow-release nutrient
Phosphorus (P)	%	1–3	Ca-P, Fe-P	Long-term availability
Potassium (K)	%	0.5–2	Exchangeable	Immediate availability
Organic Matter	%	30–60	Humic substances	Soil conditioning
Moisture Content	%	40–80	Physical	Affects application rate

Classification followed JS 1145/2016 criteria reproduced in the GIZ report. GIZ classified 24 of the 25 plants with quality tables as Class B and 1 plant, Shoubak, as Class A. These are source-reported classifications from a single sampling campaign, not a current national compliance rate. The GIZ summary states that all collected samples exceeded

pathogen limits, despite the plant-sheet classification of Shoubak as Class A. This internal source inconsistency prevents independent confirmation of the national class distribution and supports new standardized sampling.

Particular attention was given to nutrient speciation because previous studies have demonstrated that nutrient availability and heavy-metal mobility depend more strongly on chemical forms than on total concentrations [6,7].

2.6. Biosolids Generation Assessment

Current and future dry-solids production was interpreted through a component mass balance and a separate per-capita screening calculation. The component model includes primary sludge, waste biological sludge, and chemical sludge where chemical addition occurs.

- COD-based approach

$$M_{DS} = M_{PS} + M_{WAS} + M_{CS} \quad (1)$$

where M_{DS} is total dry sludge production, M_{PS} is primary-sludge dry solids, M_{WAS} is waste-activated or secondary biological dry solids, and M_{CS} is chemical-sludge dry solids. For a process without primary clarification or chemical dosing, the corresponding term equals zero. Waste biological solids may be estimated from removed biodegradable load and observed yield after accounting for endogenous decay and solids losses. The former expression, Y times COD removed, represented only biological sludge and therefore could not represent total plant sludge by itself.

- Per capita approach

$$M_{DS} = P \times r \quad (2)$$

where P is the served population and r is the reported dry-solids production factor. The screening value used in the national projection was 53 g dry solids person^{−1} day^{−1}, within the cited 40–70 g person^{−1} day^{−1} range. This method estimates total dry solids at system level. It does not separate primary, secondary, and chemical fractions.

2.7. Nutrient-Based Agronomic Assessment

Agronomic application rates were evaluated using nitrogen-based scenarios. Crop nutrient requirements (Table 4), mineralization factors, and nutrient-availability coefficients were compiled from published agronomic studies [9]. Application rates were screened against crop nitrogen demand, phosphorus loading, and site constraints.

$$AR = N_{crop} / PAN_{bio} \quad (3)$$

where AR is the biosolids application rate (t dry solids ha^{−1}), N_{crop} is crop nitrogen demand (kg N ha^{−1}), and PAN_{bio} is plant-available nitrogen supplied per tonne of dry biosolids (kg N t^{−1}).

Table 4. Crop nutrient requirements used for application rate calculations.

Crop Type	Nitrogen Requirement (kg/ha)	Phosphorus Requirement (kg/ha)	Potassium Requirement (kg/ha)
Barley	60–100	30–50	30–60
Wheat	80–120	40–60	40–80
Vegetables	120–250	60–120	80–200
Fruit trees	100–200	50–100	100–200

Plant-available nitrogen was separated into inorganic and organic pools:

$$\text{PAN}_{\text{bio}} = \text{N}_{\text{inorg,avail}} + f_m \times \text{N}_{\text{org}} \quad (4)$$

where $\text{N}_{\text{inorg,avail}}$ is the retained plant-available inorganic nitrogen, mainly NH_4^+ and NO_3^- , after relevant handling and application losses; N_{org} is organic nitrogen, and f_m is the fraction of organic nitrogen mineralized during the assessment period. Inorganic nitrogen does not undergo mineralization. It enters the available pool directly, subject to volatilization, immobilization, nitrification, denitrification, and leaching (Table 5). Only the organic nitrogen term receives the mineralization factor, commonly 0.3–0.5 for the first crop depending on treatment and site conditions [9].

Table 5. Factors affecting biosolids application rate determination [9].

Factor	Type	Influence Mechanism
Nitrogen mineralization rate (k)	Kinetic	Controls N release
Soil texture	Physical	Affects infiltration and retention
Soil pH	Chemical	Controls nutrient availability
Organic matter	Chemical	Enhances CEC and structure
Climate (temperature, rainfall)	Environmental	Controls microbial activity
Application method	Operational	Affects distribution and efficiency

Recent studies have shown that nitrogen mineralization rates are strongly influenced by soil moisture, temperature, and microbial activity, particularly in arid environments where decomposition processes are slower [3,11]. Therefore, the selected approach accounts for delayed nutrient release, which is a key characteristic of biosolids compared to synthetic fertilizers.

The analysis also considered phosphorus accumulation, potassium availability, soil texture, pH, organic matter, and climatic conditions that influence nutrient release and crop uptake. Rather than prescribing universal application rates, the assessment provides indicative recommendations based on representative crop nutrient demands.

2.8. Land Suitability Assessment

The source spatial product was described as a Boolean constraint screen. Under this framework, a location is retained only when it meets each available inclusion rule. The present study did not rerun the overlay because the original layers and project files were unavailable.

The manuscript evaluates a previously prepared Boolean spatial-screening product. Available source layers represented soil, land use, slope, groundwater depth, urban buffers, WWTP locations, Badia Restoration Program areas, and rangeland reserves. Criteria were reclassified to retain, conditional, or excluded classes as shown in Table 6. The available project archive did not contain the original GIS layers, coordinate reference system, raster resolution, resampling method, software version, overlay log, or validation sample. The map therefore serves as secondary planning evidence, not a reproducible GIS analysis conducted in this study. Protected rangeland reserves were separated from the provisional candidate area because agricultural biosolids use requires written authorization from the responsible agencies.

Jordan lacks one current national soil survey with uniform scale and date. Soil units were grouped by the texture classes used in the screening criteria [22]. Future work should rebuild the analysis from archived source layers and report the coordinate reference system, spatial resolution, software and version, reclassification rules, exclusion buffers, overlay sequence, and area-calculation procedure.

Table 6. Land suitability evaluation criteria for biosolids application according to JS 1145/2016.

Criterion	Threshold	Screening Treatment
Slope (%)	<5	Retain
Slope (%)	5–15	Conditional
Slope (%)	>15	Exclude
Soil texture	Loam to clay	Retain
Soil texture	Sand	Conditional
Groundwater depth (m)	>10	Retain
Groundwater depth (m)	5–10	Conditional, site investigation required
Groundwater depth (m)	<5	Exclude
Distance to urban area (m)	>500	Retain
Distance to urban area (m)	≤500	Exclude
Protected rangeland reserve	Any overlap	Separate from candidate area pending written authorization

2.9. Metal Compliance and Hazard Screening

For each regulated metal j , a concentration-to-limit ratio was calculated for every exact GIZ record:

$$R_j = C_j / L_j \quad (5)$$

where R_j is the screening ratio, C_j is the reported concentration in mg kg^{-1} dry solids, and L_j is the corresponding limit reproduced from JS 1145/2016. $R_j < 1$ indicates a concentration below the listed ceiling, $R_j = 1$ indicates equality, and $R_j > 1$ indicates an exceedance. This quotient is a compliance-screening ratio, not a complete ecological or human-health risk index. It does not incorporate soil background, application rate, exposure, bioavailability, or toxicity. Supplementary Table S3 reports every record-level ratio.

The ratio provides a simple comparison with the listed regulatory ceiling. Pathogen hazards were interpreted from the source classifications. Emerging contaminants were discussed qualitatively because matched national measurements were unavailable [19,20].

2.10. Uncertainty and Study Limitations

The present assessment relies primarily on secondary information compiled from published literature, governmental reports, and engineering datasets. Consequently, variations in sampling periods, analytical methodologies, wastewater treatment technologies, and reporting formats introduce unavoidable uncertainty into the synthesized results.

To minimize these limitations, information was cross-validated across multiple independent sources, and representative value ranges were used where appropriate. Nevertheless, future studies based on systematic national monitoring and long-term field experiments are needed to reduce uncertainty and validate the findings presented herein.

3. Results and Discussion

3.1. Biosolids Generation and System-Level Implications

Published projections differ substantially. USAID estimates rise from 50,947 t dry solids yr^{-1} in 2020 to 72,418 t yr^{-1} in 2035. GIZ reports 101,533–108,719 t yr^{-1} in 2020 and 128,540–149,332 t yr^{-1} in 2035. The disagreement is larger than the within-model increase and prevents selection of one national forecast. Planning should retain both scenarios until plant-level flow, influent load, solids production, treatment configuration, and sewerage coverage are updated under one mass-balance protocol.

The predominance of activated sludge technology within Jordan's wastewater treatment sector has important implications for both the quantity and quality of biosolids

generated. Activated sludge processes typically produce substantially greater quantities of excess biomass than attached-growth systems or waste stabilization ponds because microbial growth is continuously maintained under aerobic conditions. Consequently, these facilities represent the principal source of biosolids available for agricultural reuse in Jordan. Although increasing sludge production poses operational challenges related to sludge stabilization, transportation, storage, and disposal, it simultaneously provides an opportunity to recover valuable organic matter and plant nutrients through beneficial land application, thereby supporting a transition from waste management to resource recovery.

Globally, similar growth patterns have been reported in rapidly urbanizing regions, where sludge production increases in parallel with wastewater treatment coverage and improvements in sanitation services [1,2]. However, unlike many European countries where established sludge valorization pathways—including agricultural reuse, composting, anaerobic digestion, and energy recovery—have significantly reduced dependence on landfill disposal, the increasing biosolids production in Jordan remains an underutilized resource. This situation highlights the need for integrated national management strategies that prioritize resource recovery while ensuring compliance with environmental and public health regulations.

Table 7 and Figure 2 reproduce two independent national planning approaches. USAID reports plant-level projections for 2015, 2020, 2025, 2030, and 2035. The present study summed those values and converted kg d^{-1} to t yr^{-1} . GIZ reports national ranges of 101,533–108,719 t dry matter in 2020 and 128,540–149,332 t in 2035, based on observed yield, flow, and load calculations. The large gap between the scenarios reflects different plant coverage, system boundaries, treatment assumptions, and coefficients. No intermediate GIZ values were interpolated.

Table 7. (a). Synthesized biosolids generation trends in Jordan. (b). Scenario uncertainty in national biosolids-generation estimates.

(a)			
Source Scenario	2020 (t DS yr ⁻¹)	2035 (t DS yr ⁻¹)	Scope and Calculation
GIZ lower estimate	101,533	128,540	Observed yield and load calculations across operating plants
GIZ upper estimate	108,719	149,332	Upper bound from plant calculations
USAID	50,947	72,418	$\text{kg d}^{-1} \times 365/1000$
(b)			
Comparison	Lower Value (t yr ⁻¹)	Upper Value (t yr ⁻¹)	Relative Difference
USAID vs. GIZ lower, 2020	50,947	101,533	−49.8%
USAID vs. GIZ lower, 2035	72,418	128,540	−43.7%
GIZ range width, 2020	101,533	108,719	7.1% of lower estimate
GIZ range width, 2035	128,540	149,332	16.2% of lower estimate

From a systems perspective, the projected increase in biosolids generation represents not only a waste management challenge but also a strategic opportunity for implementing circular economy principles within the wastewater sector [6]. Rather than considering sewage sludge as a disposal burden, biosolids can be regarded as a renewable secondary resource that recycles nutrients and organic matter back into agricultural production systems, reduces waste destined for landfill, and contributes to more sustainable wastewater management. Future increases in biosolids production anticipated by 2035 further emphasize the importance of developing integrated national policies that combine sludge

stabilization, quality assurance, nutrient recovery, land suitability assessment, and long-term environmental monitoring to maximize agronomic benefits while safeguarding soil, water resources, and human health.

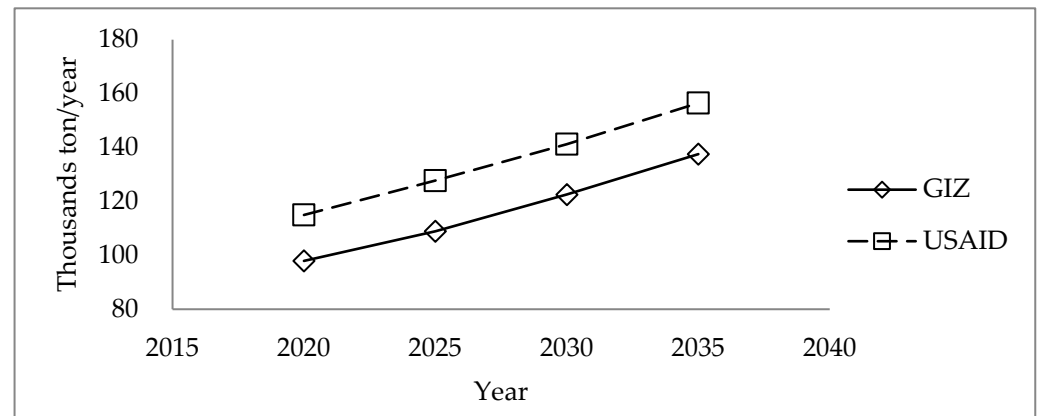


Figure 2. Published biosolids-generation scenarios for Jordan. USAID values are sums of plant projections of the Kingdom-Wide Biosolids Management Strategy, converted from kg d^{-1} to $\text{t dry solids yr}^{-1}$. GIZ values reproduce the national 2020 and 2035 ranges reported in the Sludge Mapping in Jordan executive summary [43–45]. No regression or interpolation was fitted.

3.2. Physicochemical Characteristics and Chemical Speciation

The two national reports provide quantitative evidence at different levels of coverage. GIZ surveyed 29 operational WWTPs and reported sludge-quality tables for 25 plants. Multiple stages at As-Samra, Mutah-Mazar, and Kufranja produced 28 stage-specific records. USAID reported heavy-metal concentrations for nine plants and six nutrient grab samples from Al Baqa'a, Fuhais, and Aqaba Mechanical. These data support descriptive analysis, but they do not form one balanced 33-plant dataset.

GIZ reported no concentration above the listed ceilings for Cd, Pb, Zn, or Cu. The maximum concentration-to-limit ratios were 1.000 for Cd, 0.103 for Pb, 0.525 for Zn, and 0.377 for Cu. The maximum Cd value equaled its ceiling, so the result does not support a broad claim of negligible chemical risk. These ratios provide transparent regulatory screening only. They do not establish long-term safety after repeated application.



where M represents divalent metal ions such as Cd^{2+} , Cu^{2+} , Ni^{2+} , Pb^{2+} , and Zn^{2+} . In addition to precipitation, these metals are strongly adsorbed onto organic matter, iron and manganese oxides, and clay mineral surfaces, further reducing their mobility, bioavailability, and subsequent plant uptake [15]. Therefore, despite repeated biosolids applications, the alkaline nature of Jordanian soils provides an important geochemical barrier that limits heavy metal migration into the soil solution and reduces the potential risk to crops and [43–45] groundwater. Nevertheless, long-term monitoring remains necessary because gradual changes in soil pH, organic matter decomposition, or repeated biosolids loading may alter metal speciation and increase metal availability over time.

In contrast to the favorable chemical characteristics, microbiological quality remains the principal constraint limiting widespread agricultural reuse of biosolids in Jordan. The available evidence indicates that most biosolids are classified as Class B, primarily because current sludge stabilization practices rely heavily on passive drying and conventional dewatering processes that achieve only partial pathogen reduction. Similar observations have been reported in previous studies demonstrating that passive stabilization methods, including solar drying beds, are often insufficient to achieve complete inactivation of bacterial

pathogens, viruses, and helminth ova under fluctuating environmental conditions [4,17]. Consequently, additional treatment technologies such as composting, thermophilic anaerobic digestion, alkaline stabilization, thermal drying, or advanced hygienization processes may be required to consistently achieve Class A biosolids suitable for unrestricted agricultural application.

The available literature identifies microbiological quality as a recurring barrier to unrestricted reuse (Table 8). Chemical risk also requires batch-specific evidence. The national archive used here does not support a blanket statement that heavy-metal limitations are minor across all plants. Management should combine validated pathogen reduction with routine measurement of regulated metals and cumulative loading.

Table 8. (a). Synthesized chemical composition and speciation of biosolids. (b). Descriptive statistics for heavy metals reported in the GIZ sludge-mapping dataset [43–45]. (c). Descriptive statistics for individual nutrient grab samples reported by USAID [43–45].

(a)						
Parameter	Typical Range	Dominant Form	Bioavailability	Agronomic/Environmental Implication		
Nitrogen (N)	Moderate–High	Organic N, NH ₄ ⁺	Medium (controlled release)	Slow nutrient release		
Phosphorus (P)	High	Ca–P, Fe–P	Low–Moderate	Risk of accumulation		
Potassium (K)	Moderate	Exchangeable K ⁺	High	Immediate availability		
Organic matter	High	Humic substances	High	Improves soil structure		
Heavy metals	Low	Carbonate/organic-bound	Low	Limited mobility		
Pathogens	High (Class B)	Biological	High risk	Requires treatment		
(b)						
Metal	n Exact	Mean ± SD (mg kg ^{−1} DS)	Range (mg kg ^{−1} DS)	JS limit	Mean Rj	Maximum Rj
Cd	27	3.44 ± 7.45	0–40	40	0.086	1.000
Pb	27	7.93 ± 7.25	0–31	300	0.026	0.103
Zn	28	603.79 ± 377.27	0–1470	2800	0.216	0.525
Cu	28	111.86 ± 114.67	0–565	1500	0.075	0.377
(c)						
Parameter	Unit	n	Mean	SD	Minimum	Maximum
Moisture	%	6	98.00	1.39	95.60	99.40
Total N	%	6	3.93	2.42	0.82	7.29
Total P	%	6	1.71	0.98	0.77	3.42
Total K	%	6	0.71	0.35	0.32	1.16
Total volatile solids	%	5	74.86	3.18	70.10	78.40

Note: GIZ values printed in mg g^{-1} were converted to mg kg^{-1} dry solids. Censored values were excluded from numerical summaries. Values printed as 0.000 were retained as reported. Note: USAID Table 3-7 reports two grab samples from each of three WWTPs. Organic matter was reported only as an aggregate range of 51.35–74.45%, with an average of 66%, and was not assigned to individual plants. Plant-specific pH was not reported.

3.3. Nutrient Transformation and Agronomic Efficiency

The agronomic value of biosolids depends not only on their total nutrient content but also on the physicochemical and biological processes that regulate nutrient availability following land application. Unlike synthetic fertilizers, where nutrients are immediately available, the majority of nutrients contained in biosolids are gradually released through

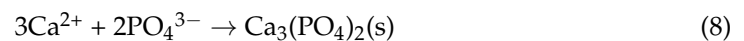
microbial decomposition and mineralization. Consequently, nutrient availability is controlled by interactions among biosolids characteristics, soil properties, climatic conditions, and crop nutrient demand, making nutrient transformations a critical factor in determining fertilizer efficiency and environmental performance.

Organic nitrogen mineralization was represented by first-order kinetics. Inorganic NH_4^+ and NO_3^- were excluded from the mineralizable pool:

$$N_t = N_0(1 - e^{kt}) \quad (7)$$

where N_t is cumulative nitrogen mineralized from the organic pool by time t , N_0 is potentially mineralizable organic nitrogen, and k is the first-order mineralization constant. This equation does not describe inorganic nitrogen. Temperature, moisture, aeration, substrate quality, and microbial activity control k .

In calcareous soils, orthophosphate forms react with calcium. The following balanced reaction illustrates precipitation of tricalcium phosphate:



This precipitation reaction reduces the immediate availability of phosphorus while simultaneously increasing its long-term retention within the soil [26–42]. Consequently, phosphorus supplied through biosolids behaves as a slow-release nutrient that can provide residual fertility over multiple growing seasons. In addition, the high organic matter content of biosolids partially mitigates phosphorus fixation by forming soluble organo-metal complexes, competing for adsorption sites, and stimulating microbial activity that promotes phosphorus solubilization. These mechanisms improve phosphorus availability compared with inorganic phosphorus fertilizers applied to highly calcareous soils, although the extent of this improvement depends on soil pH, carbonate content, and biological activity.

The six USAID samples averaged $3.93 \pm 2.42\%$ total N, $1.71 \pm 0.98\%$ total P, and $0.71 \pm 0.35\%$ total K [43–45]. Table 9 shows the consequences of composition and mineralization uncertainty for a crop requiring 100 kg available N ha^{-1} . Assuming the measured total N is organic for conservative screening, the estimated biosolids rate spans 2.74–40.65 t dry solids ha^{-1} . At the mean-N scenario and a 0.40 first-year mineralization fraction, the rate is 6.36 t ha^{-1} and supplies about 108.8 kg P ha^{-1} . Crop-specific application therefore requires measured inorganic N, organic N, dry solids, soil-test P, salinity, and crop demand. The earlier universal claims of 60–200% nutrient coverage and an optimum rate of 30–50 t ha^{-1} were removed.

Table 9. Worked nitrogen-rate scenarios using the observed USAID total-N range [43–45].

Total N in Biosolids (%)	First-Year Mineralization Fraction	Plant-Available N (kg t^{-1} DS)	Rate for 100 kg N ha^{-1} (t DS ha^{-1})	P Applied at 1.71% P (kg ha^{-1})
0.82	0.30	2.46	40.65	695.1
3.93	0.40	15.72	6.36	108.8
7.29	0.50	36.45	2.74	46.9

From a practical perspective, these findings suggest that biosolids application rates should be determined using integrated nutrient management approaches that consider crop nutrient requirements, existing soil fertility, phosphorus accumulation potential, and site-specific environmental conditions. Where repeated applications are planned, periodic soil testing and nutrient budgeting should be incorporated into management programs to optimize fertilizer replacement while minimizing nutrient losses and maintaining compliance with environmental regulations. Such strategies maximize the agronomic benefits

of biosolids while supporting circular nutrient recovery and sustainable soil management under Jordan's water-limited conditions.

3.4. Soil–Chemical Interactions and Productivity Enhancement

The application of biosolids significantly improves soil physicochemical properties through the addition of organic carbon and reactive functional groups. The increase in soil organic matter enhances cation exchange capacity (CEC), which is directly related to the density of negative charge sites:

$$\text{CEC} \propto \text{OM} \quad (9)$$

where OM represents soil organic matter content. As the organic matter content increases, additional negatively charged carboxylic and phenolic functional groups become available for cation adsorption, thereby enhancing the soil's capacity to retain essential nutrients such as ammonium (NH_4^+), potassium (K^+), calcium (Ca^{2+}), and magnesium (Mg^{2+}). Consequently, biosolids application increases nutrient retention, improves soil buffering capacity, reduces nutrient leaching losses, and enhances nutrient availability throughout the growing season. These improvements are particularly important in Jordanian soils, which are generally characterized by low organic matter content, moderate clay contents, and limited nutrient-holding capacity.

Beyond their influence on soil chemistry, biosolids substantially improve soil physical properties through the formation of stable organo-mineral complexes. Organic matter interacts with clay minerals and polyvalent cations to promote aggregate formation, resulting in improved soil structure, increased porosity, lower bulk density, enhanced infiltration, and greater water-holding capacity. These changes improve root penetration, increase soil aeration, and reduce surface crusting and erosion. Such improvements are particularly beneficial under Jordan's semi-arid climatic conditions, where limited rainfall, high evapotranspiration rates, and frequent soil moisture deficits constrain agricultural productivity. Increasing the soil's capacity to retain water therefore contributes directly to improved irrigation efficiency and greater resilience to drought stress.

The improved physicochemical environment also stimulates soil biological activity by providing energy and carbon substrates for microorganisms responsible for nutrient cycling and organic matter decomposition. Enhanced microbial activity accelerates nutrient mineralization, promotes soil aggregation through microbial exudates, and contributes to the long-term development of healthy and productive soils. Consequently, the benefits of biosolids extend beyond simple nutrient addition by improving overall soil functioning and supporting sustainable agricultural production.

Experimental studies conducted in Jordan demonstrate substantial improvements in soil organic matter content, water-use efficiency, and crop productivity following biosolids application. Similar findings have been reported for other Mediterranean and semi-arid environments, where biosolids significantly improved soil hydraulic properties, increased available water storage, reduced drought stress, and enhanced crop performance under water-limited conditions [26,43–47]. These observations highlight the dual role of biosolids as both an organic soil amendment and a slow-release nutrient source, making them particularly valuable in regions facing increasing water scarcity and declining soil fertility.

Published Jordanian field and pot studies report crop and soil responses under different amendments, rates, soils, and durations [27–40]. Their outcomes were not pooled because treatment definitions and statistical designs were heterogeneous. Table 10 therefore reports a transparent loading screen instead of broad percentage ranges. The calculation assumes $6.36 \text{ t dry solids ha}^{-1} \text{ yr}^{-1}$ for ten years, no removal or loss, the USAID mean P concentration, and GIZ mean metal concentrations. It is a conservative mass-input screen rather than a prediction of soil concentration or crop uptake.

Table 10. Ten-year loading screen for the mean-N application scenario.

Constituent	Annual Input at 6.36 t DS ha ⁻¹	10-Year Input Without Loss	Interpretation
Phosphorus	108.8 kg P ha ⁻¹	1088 kg P ha ⁻¹	Requires soil-test P control
Cadmium	21.9 g ha ⁻¹	219 g ha ⁻¹	Maximum batch result reached the ceiling
Lead	50.4 g ha ⁻¹	504 g ha ⁻¹	Track cumulative loading
Zinc	3.84 kg ha ⁻¹	38.4 kg ha ⁻¹	Largest metal mass input
Copper	0.71 kg ha ⁻¹	7.11 kg ha ⁻¹	Track cumulative loading
Soluble salts	Not calculated	Not calculated	EC or total-solids data were unavailable on a matched dry basis

Overall, the results indicate that biosolids application provides substantial agronomic benefits through simultaneous improvements in soil fertility, physical structure, biological activity, and water-use efficiency. Nevertheless, maximizing these benefits requires site-specific application rates based on soil characteristics, crop nutrient requirements, irrigation practices, and long-term monitoring of soil salinity and nutrient status. Such integrated management approaches enable biosolids to function as an effective component of sustainable nutrient management while minimizing environmental risks and supporting circular economy objectives in Jordanian agriculture, as shown in Table 10.

3.5. Spatial Suitability and Land Application Potential

The source spatial product mapped 9364.60 km² of Badia Restoration Program rangelands, 745.62 km² of protected rangeland reserves, and 40.06 km² near WWTPs. Their correct sum is 10,150.28 km². Because the reserves require separate legal authorization, the provisional non-reserve area is 9404.66 km². Neither value represents field-verified suitability.

The predominance of rangelands within the suitable area is consistent with the widespread occurrence of degraded soils characterized by low organic matter content, poor aggregate stability, and limited natural fertility. These soils exhibit the greatest potential for improvement following organic amendments because the addition of biosolids simultaneously increases soil organic carbon, improves aggregate formation, enhances infiltration, increases water-holding capacity, and stimulates biological activity. Consequently, the relative agronomic benefits are expected to be considerably greater in degraded rangelands than in productive agricultural soils that already possess higher levels of soil fertility.

The Badia Restoration Program area represents a planning envelope for further assessment. Protected rangeland reserves were excluded from the provisional candidate total pending written authorization. Areas near WWTPs also require buffer checks, land-status confirmation, and field verification before any reuse decision.

Land suitability was not determined solely by soil fertility but also by environmental protection criteria. Areas with steep slopes, shallow groundwater, urban expansion, environmentally sensitive ecosystems, or high runoff potential were excluded from biosolids application because of the increased risks of nutrient transport, pathogen migration, and groundwater contamination. Consequently, the spatial assessment balances agronomic benefits with environmental protection, ensuring that biosolids application is directed toward locations where long-term sustainability can be maximized while minimizing potential environmental impacts.

The compiled evidence further indicates that biosolids application is particularly beneficial in arid and semi-arid regions where soil degradation is widespread. Similar findings have been reported in Mediterranean and dryland ecosystems, where repeated biosolids application increased soil organic carbon, improved soil hydraulic properties,

enhanced water-use efficiency, promoted vegetation establishment, and accelerated ecosystem restoration [25]. These observations are highly relevant to Jordan, where more than 90% of the country is classified as arid or semi-arid and declining soil quality represents a major limitation to sustainable agricultural production.

The spatial output identifies a broad planning envelope, not approved application sites. The gross mapped area is 10,150.28 km². Excluding protected reserves leaves 9404.66 km² for additional screening. Site approval requires verified biosolids quality, land ownership and protection status, groundwater depth, slope, runoff risk, soil and crop suitability, access, application-rate controls, and field inspection, as shown in Table 11 and Figure 3.

Table 11. Reported spatial-screen classes and corrected areas.

Land Class	Area (km ²)	Regulatory Interpretation
Badia Restoration Program rangelands	9364.60	Candidate only after agency and field review
Protected rangeland reserves	745.62	Excluded from provisional candidate total pending written authorization
Areas near WWTPs	40.06	Candidate only after field and buffer verification
Gross mapped screen	10,150.28	Arithmetic sum of the three source classes
Provisional non-reserve screen	9404.66	Gross screen minus protected reserves

3.6. Environmental Hazards and Regulatory Screening

The environmental behavior of biosolids-derived contaminants is primarily controlled by chemical partitioning, transformation processes, soil properties, application frequency, and post-application environmental conditions. The synthesized evidence indicates that heavy metals in Jordanian biosolids generally exhibit low short-term mobility under alkaline and calcareous soil conditions because of adsorption onto organic matter, clay minerals, and metal oxides, as well as precipitation reactions that reduce dissolved metal concentrations [15,48–50]. However, this low mobility should not be interpreted as absence of risk. Because heavy metals are persistent and non-biodegradable, repeated biosolids applications may lead to gradual accumulation in surface soils over time. Therefore, long-term monitoring of metal loading rates, background soil concentrations, soil pH, and crop uptake is required before unrestricted reuse can be recommended.

Pathogen persistence remains a more immediate limitation for agricultural application. Pathogen decline following biosolids treatment and land application can be described using first-order decay kinetics:

$$N_t = N_0 e^{-kt} \quad (10)$$

where N_t is the pathogen concentration at time t , N_0 is the initial pathogen concentration, and k is the first-order decay constant. This conceptual equation interprets published observations. The study did not estimate k from original microbiological measurements. Temperature, moisture, solar radiation, pH, storage time, and stabilization method affect the value of k . Current evidence identifies pathogen persistence as the main restriction on broad agricultural use. Improved composting, thermophilic digestion, alkaline stabilization, thermal drying, or another validated hygienization step is required where unrestricted use is sought. Emerging contaminants were assessed separately because national monitoring remains incomplete.

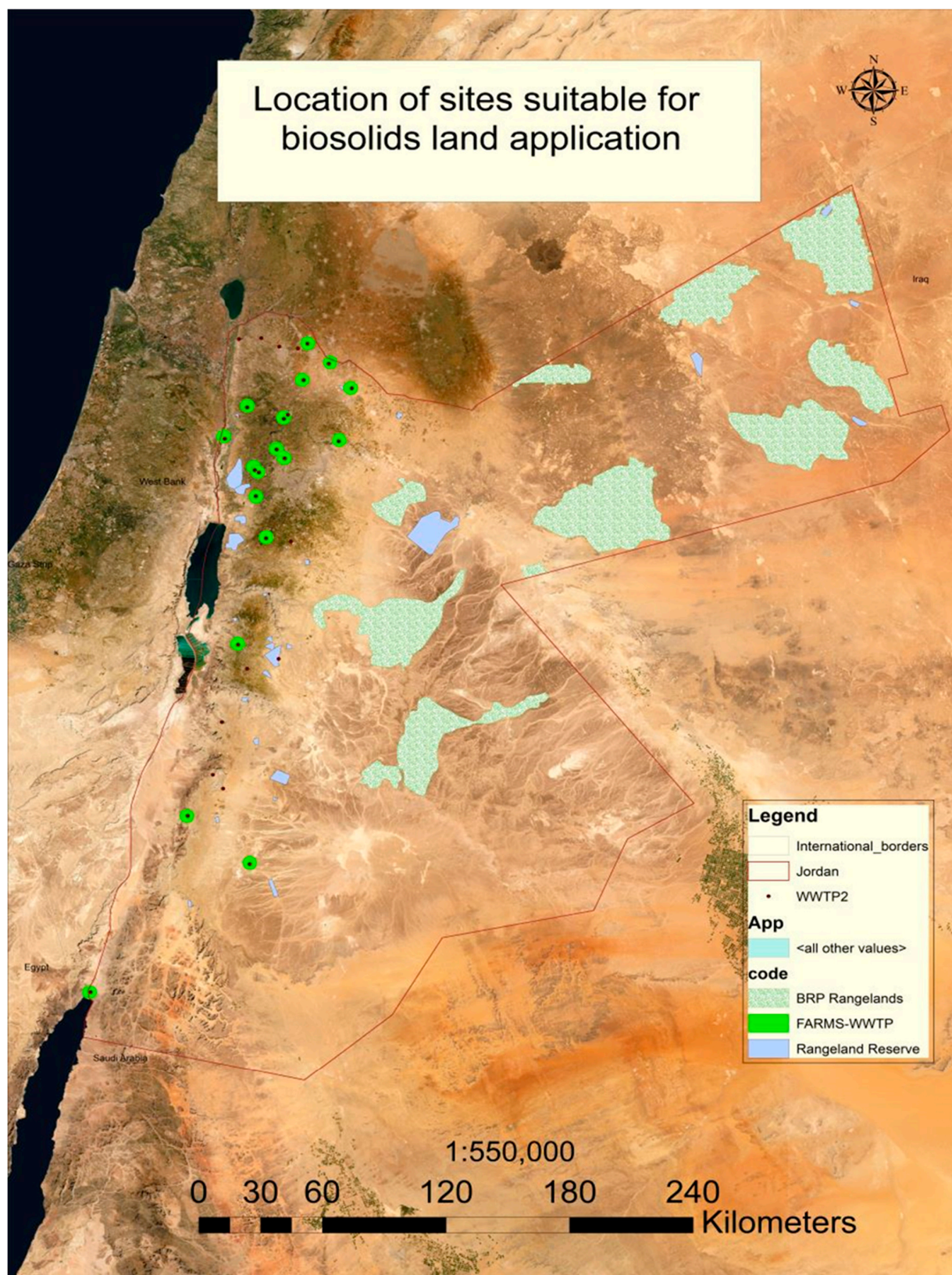


Figure 3. Previously prepared spatial-screening map for biosolids application in Jordan. The figure is reproduced as secondary planning evidence. Source layers and processing metadata were not preserved in the manuscript archive, so the map was not independently reproduced or validated. Protected rangeland reserves require separate regulatory authorization [42,48–50].

$$K_d = C_{\text{solid}}/C_{\text{solution}} \quad (11)$$

where K_d is the solid/water distribution coefficient, C_{solid} is the contaminant concentration associated with solids, and C_{solution} is the dissolved concentration. A higher K_d indicates stronger short-term retention. Strong sorption does not prove degradation and may increase persistence in amended soil.

The available data support a regulatory screening of four metals and a narrative identification of pathogen and emerging-contaminant hazards. They do not support a complete quantitative environmental risk assessment. Metal ratios remained at or below 1.0, but repeated loading, soil background, exposure, and bioavailability were not measured. GIZ source classifications and pathogen measurements identify pathogen reduction as the immediate reuse constraint. Emerging contaminants require a dedicated monitoring program because national occurrence data remain incomplete.

3.7. Integrated Interpretation and Implications

The integrated evidence identifies nutrient-recovery potential alongside substantial data gaps. The available composition data support crop-specific screening. They do not establish unrestricted safety, a national optimum application rate, or validated land suitability. Decisions should remain conditional on batch analysis, pathogen verification, soil testing, cumulative loading controls, and current spatial data.

From an engineering and sustainability perspective, biosolids reuse offers a practical pathway for shifting sludge management from disposal toward circular resource recovery. Nevertheless, this transition requires more than land availability or nutrient value alone. It requires improved sludge stabilization technologies, clear classification according to JS 1145/2016, nutrient application plans based on both nitrogen and phosphorus demand, and long-term monitoring of soil quality, pathogen indicators, heavy metals, salinity, and emerging contaminants.

Overall, the findings indicate that biosolids reuse can contribute to sustainable soil management and agricultural productivity in Jordan, particularly in degraded and low-organic-matter soils. However, national-scale implementation should be approached cautiously and supported by verified datasets, site-specific risk assessment, and continuous monitoring. This balanced interpretation recognizes the agronomic value of biosolids while addressing the key limitations identified by the reviewers regarding data uncertainty, pathogen risk, long-term accumulation, and the need for stronger technical and regulatory controls.

4. Conclusions

This assessment separates Jordan's current 33-WWTP inventory from the historical analytical coverage of the national reports. GIZ reported quality data for 25 plants, comprising 28 plant-stage records. USAID reported metal data for nine plants and six nutrient samples from three plants. These sources do not form a complete matched national dataset. GIZ mean metal concentrations were 3.44 mg Cd kg⁻¹, 7.93 mg Pb kg⁻¹, 603.79 mg Zn kg⁻¹, and 111.86 mg Cu kg⁻¹ dry solids. Maximum concentration-to-limit ratios were 1.000, 0.103, 0.525, and 0.377, respectively. These results support batch-level regulatory screening, but they do not establish long-term ecological safety. The reported pathogen classifications identify treatment and verification as the first condition for wider agricultural reuse. Generation estimates remain model-dependent. GIZ estimated 101,533–108,719 t dry solids yr⁻¹ in 2020 and 128,540–149,332 t yr⁻¹ in 2035. USAID estimated 50,947 and 72,418 t yr⁻¹. Planning should therefore use scenario ranges and plant-level mass balances. The corrected gross spatial screen is 10,150.28 km². Excluding protected reserves leaves 9404.66 km² for

regulatory and field evaluation. Jordan should prioritize standardized plant sampling, validated pathogen reduction, crop-specific nitrogen and phosphorus budgets, cumulative metal and salt monitoring, and a documented GIS rerun using current layers. These actions would convert the present planning evidence into a defensible national reuse program.

Supplementary Materials: Supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/agronomy16191904/s1>, Table S1: GIZ Plant-Stage Metal Records; Table S2: Record-Level Metal Screening Ratios; Table S3: USAID Nutrient Grab Samples; Table S4: USAID Plant-Level Biosolids Projections; Table S5: National Generation Scenario Summary; Table S6: Nutrient Rate and Ten-Year Loading Calculations.

Author Contributions: Conceptualization, N.O. and A.S.; methodology, N.O. and A.S.; software, N.O. and A.S.; validation, N.O., A.S., A.A.A. and J.Y.M.A.; formal analysis, N.O., R.H.A.O., O.A.D., M.Z. and A.S.; investigation, N.O., A.S., N.B.H. and R.S.T.; resources, N.O., A.S. and N.B.H.; data curation, N.O., A.S. and S.J.; writing—original draft preparation, N.O. and A.S.; writing—review and editing, N.O., A.S., A.A.A., J.Y.M.A., N.B.H., R.S.T. and S.J.; visualization, N.O., A.S., R.H.A.O., O.A.D., M.Z. and S.J.; supervision, N.O. and A.S.; project administration, N.O. and A.S.; funding acquisition, A.S. and N.O. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ), Sustainable Sludge Management in Jordan Project, grant number PN:2019.2325.9.

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

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

Abbreviations

The following abbreviations are used in this manuscript:

AEZs	Agro-Ecological Zones
AR	Application Rate
AS	Activated Sludge
Ca–P	Calcium Phosphate
CEC	Cation Exchange Capacity
COD	Chemical Oxygen Demand
DS	Dry Solids
FAO	Food and Agriculture Organization
Fe–P	Iron-Bound Phosphorus
JS	Jordanian Standard
K	Potassium
Kd	Distribution Coefficient
N	Nitrogen
NH ₄ ⁺	Ammonium
NO ₃ [−]	Nitrate
OM	Organic Matter
P	Phosphorus
PFAS	Per- and Polyfluoroalkyl Substances
RI	Risk Index
SDGs	Sustainable Development Goals
TN	Total Nitrogen
USEPA	United States Environmental Protection Agency
VSS	Volatile Suspended Solids
WSP	Waste Stabilization Pond
WWTP	Wastewater Treatment Plant
WUE	Water-Use Efficiency

References

- Collivignarelli, M.C.; Abbà, A.; Benigna, I. The reuse of biosolids on agricultural land: Critical issues and perspective. *Water Environ. Res.* **2020**, *92*, 11–25. [CrossRef] [PubMed]
- Ezeh, E.M.; Agu, P.C. Recent Advances in Sludge Management: An Overview. *Mater. Circ. Econ.* **2026**, *8*, 3. [CrossRef]
- Elgarahy, A.M.; Eloffy, M.G.; Priya, A.K.; Yogeshwaran, V.; Yang, Z.; Elwakeel, K.Z.; López-Maldonado, E.A. Biosolids management and utilization: A review. *J. Clean. Prod.* **2024**, *451*, 141974. [CrossRef]
- Pozzebon, E.A.; Seifert, L. Emerging environmental health risks associated with the land application of biosolids: A scoping review. *Environ. Health* **2023**, *22*, 57. [CrossRef] [PubMed]
- Almashaqbeh, O.; Emmanouil, C.; Alsalhi, L. Quantification of pharmaceuticals in sludge produced from wastewater treatment plants in Jordan and environmental risk assessment. *Toxics* **2026**, *14*, 62. [CrossRef] [PubMed]
- Marchuk, S.; Tait, S.; Sinha, P.; Harris, P.; Antille, D.L.; McCabe, B.K. Biosolids-derived fertilisers: A review of challenges and opportunities. *Sci. Total Environ.* **2023**, *875*, 162555. [CrossRef] [PubMed]
- Nunes, N.; Ragonezi, C.; Gouveia, C.S.; Pinheiro de Carvalho, M.Â. Review of sewage sludge as a soil amendment in relation to current international guidelines: A heavy metal perspective. *Sustainability* **2021**, *13*, 2317. [CrossRef]
- Balkrishna, A.; Kaushik, P.; Singh, S.; Agrahari, P.; Kumar, B.; Kumar, P.; Arya, V.P. Potential use of sewage sludge as fertilizer in organic farming. *Clean. Waste Syst.* **2025**, *10*, 100245. [CrossRef]
- Rigby, H.; Clarke, B.O.; Pritchard, D.L.; Meehan, B.; Beshah, F.; Smith, S.R.; Porter, N.A. A critical review of nitrogen mineralization in biosolids-amended soil, the associated fertilizer value for crop production and potential for emissions to the environment. *Sci. Total Environ.* **2016**, *541*, 1310–1338. [CrossRef] [PubMed]
- Hassouneh, O.; Jamrah, A.; Qaisi, K. Sludge stabilization by composting: A Jordanian case study. *Bioprocess Biosyst. Eng.* **1999**, *20*, 413–421. [CrossRef]
- Suleiman, W.T.; Gerba, C.P.; Tamimi, A.H.; Hayek, B. Management practices of sludge and biosolid treatment and disposal in Jordan. *J. Residuals Sci. Technol.* **2010**, *7*, 63–67.
- Ababsa, N.; Fellah, S.; Boudjabi, S.; Lallaouna, R.; Sifi, M.; Bessaih, M.; Chenchouni, H. Field applications of sewage sludge improved soil properties and increased wheat yield in sand-textured soils of hot drylands. *Biodegradation* **2026**, *37*, 29. [CrossRef] [PubMed]
- Kabir, A.H.; Baki, M.Z.I.; Ahmed, B.; Mostofa, M.G. Current, faltering, and future strategies for advancing microbiome-assisted sustainable agriculture and environmental resilience. *N. Crops* **2024**, *1*, 100013. [CrossRef]
- Shi, X.; Zhao, Y.; Xu, M.; Ma, L.; Adams, J.M.; Shi, Y. Insights into plant–microbe interactions in the rhizosphere to promote sustainable agriculture in the new crops era. *N. Crops* **2024**, *1*, 100004. [CrossRef]
- Basta, N.T.; Ryan, J.A.; Chaney, R.L. Trace element chemistry in residual-treated soil: Key concepts and metal bioavailability. *J. Environ. Qual.* **2005**, *34*, 49–63. [CrossRef] [PubMed]
- Heras, J.D.L.; Mañas, P.; Labrador, J. Effects of several applications of digested sewage sludge on soil and plants. *J. Environ. Sci. Health* **2007**, *40*, 437–451. [CrossRef] [PubMed]
- Lu, Q.; He, Z.L.; Stoffella, P.J. Land application of biosolids in the USA: A review. *Appl. Environ. Soil. Sci.* **2012**, *1*, 201462. [CrossRef]
- Ng, E.L.; Huerta Lwanga, E.; Eldridge, S.M.; Johnston, P.; Hu, H.W.; Geissen, V.; Chen, D. An overview of microplastic and nanoplastic pollution in agroecosystems. *Sci. Total Environ.* **2018**, *627*, 1377–1388. [CrossRef] [PubMed]
- Kumar, M.; Xiong, X.; He, M.; Tsang, D.C.W.; Gupta, J.; Khan, E.; Harrad, S.; Hou, D.; Ok, Y.S.; Bolan, N.S. Microplastics as pollutants in agricultural soils. *Environ. Pollut.* **2020**, *265*, 114980. [CrossRef] [PubMed]
- Arab, M.; Yu, J.; Nayebe, B. Microplastics in sludges and soils: A comprehensive review on distribution, characteristics, and effects. *Chem. Eng.* **2024**, *8*, 86. [CrossRef]
- Kayal, B.; Massoud, M.; Nicolescu, C.M. Integrated system dynamics approach to wastewater management in Jordan: Balancing environmental compliance and economic sustainability. *Resour. Conserv. Recycl. Adv.* **2026**, *30*, 200341. [CrossRef]
- Al Qudah, B. Soils of Jordan. In *Soil Resources of Southern and Eastern Mediterranean Countries*; Zdruli, P., Steduto, P., Lacirignola, C., Montanarella, L., Eds.; Ciheam: Bari, Italy, 2001; pp. 127–141. Available online: <http://om.ciheam.org/om/pdf/b34/01002090.pdf> (accessed on 4 April 2025).
- He, Z.; Zhang, P.; Jia, H.; Zhang, S.; Nishawy, E.; Sun, X.; Dai, M. Regulatory mechanisms and breeding strategies for crop drought resistance. *N. Crops* **2024**, *1*, 100029. [CrossRef]
- Jiménez, B.; Drechsel, P.; Koné, D.; Bahri, A.; Raschid-Sally, L.; Qadir, M. Wastewater, sludge and excreta use in developing countries: An overview. In *Wastewater Irrigation and Health*; Earthscan: Barcelona, Spain, 2009; pp. 3–27.
- Chagas, J.K.M.; Nardoto, G.B.; Madari, B.E.; de Figueiredo, C.C. Seven-year effects of sewage sludge biochar on soil organic carbon pools and yield: Understanding the role of biochar on carbon sequestration and productivity. *Soil. Use Manag.* **2024**, *40*, e70001. [CrossRef]

26. Seleiman, M.; Santanen, A.; Mäkelä, P. Recycling sludge on cropland as fertilizer—Advantages and risks. *Resour. Conserv. Recycl.* **2020**, *155*, 104647. [\[CrossRef\]](#)
27. Abu-Sharar, T.M. Effects of sewage sludge treatments on aggregate slaking, clay dispersion and hydraulic conductivity of a semi-arid soil sample. *Geoderma* **1993**, *59*, 327–343. [\[CrossRef\]](#)
28. Abu-Sharar, T.M. Modification of hydraulic properties of a semiarid soil in relation to seasonal applications of sewage sludge and electrolyte-producing compounds. *Soil. Technol.* **1996**, *9*, 1–13. [\[CrossRef\]](#)
29. Abu-Sharar, T.M.; Hussein, I.A.; Al-Jayyousi, O.R. The use of treated sewage for irrigation in Jordan: Opportunities and constraints. *Water Environ. J.* **2003**, *17*, 232–238. [\[CrossRef\]](#)
30. Rawajfih, Z.; Gharaibeh, S. High rates of domestic sewage sludge on a calcareous soil and their effect on wheat growth using a pot experiment. *Z. Pflanzenernaehr. Bodenk.* **1990**, *153*, 297–300. [\[CrossRef\]](#)
31. Abu-Zanat, M.W.; Ruyle, G.B.; Abdel-Hamid, N.F. Increasing range production from fodder shrubs in low rainfall areas. *J. Arid. Environ.* **2004**, *59*, 205–216. [\[CrossRef\]](#)
32. Mohammad, M.J.; Athamneh, B.M. Changes in soil fertility and plant uptake of nutrients and heavy metals in response to sewage sludge application to calcareous soils. *J. Agron.* **2004**, *3*, 229–236. [\[CrossRef\]](#)
33. Hussein, I.A.J.; Abu-Sharar, T.M.; Mrayyan, B. Assessment of the application of treated wastewater and sewage sludge in productive agriculture: A case study from northern Jordan. *Water Environ. J.* **2007**, *19*, 394–403. [\[CrossRef\]](#)
34. El-Motaium, R.A.; El-Seoud, M.A.A. Irradiated sewage sludge for production of fennel plants in sandy soil. *Nutr. Cycl. Agroecosyst.* **2007**, *78*, 133–142. [\[CrossRef\]](#)
35. Tamimi, A.H.; Athamneh, B.; Gerba, C.P.; Suleiman, W. Biosolids Application for Barley Production. *J. Residuals Sci. Technol.* **2016**, *13*, 153–164. [\[CrossRef\]](#) [\[PubMed\]](#)
36. Athamneh, B.M.; Salem, N.M.; El-Zuraiqi, S.M.; Suleiman, W.; Rusan, M.J. Combined land application of treated wastewater and biosolids enhances crop production and soil fertility. *Desalin. Water Treat.* **2015**, *53*, 3283–3294. [\[CrossRef\]](#)
37. Faria, W.M.; Figueiredo, C.C.D.; Coser, T.R.; Vale, A.T.; Schneider, B.G. Is sewage sludge biochar capable of replacing inorganic fertilizers for corn production? Evidence from a two-year field experiment. *Arch. Agron. Soil. Sci.* **2018**, *64*, 505–519. [\[CrossRef\]](#)
38. Al Ayyash, S.M.; Al-Meshan, O.M.; Shatnawi, R.S. Application of Bio-Solids as Soil Amendment in Arid Rangeland of Jordan. *J. Environ. Prot.* **2017**, *8*, 344–357. [\[CrossRef\]](#)
39. Aukour, F.J.; Bani Hani, N. Plant biomass and water use efficiency of winter barley (*Hordeum vulgare* L.) under biosolid applications. *Water Sci. Technol.* **2022**, *85*, 2350–2357. [\[CrossRef\]](#) [\[PubMed\]](#)
40. Aukour, F.J.; Hani, N.B.; Al-Kofahi, S.D.; Smeir, S.A. The Effects of Biosolid Application on Water-Use Efficiency and the Growth Behavior of *Sesbania sesban* (L.) Merr in Arid Mediterranean Environments. *JJEES* **2018**, *9*, 134.
41. Al-Addous, M.; Bdour, M.; Alnaief, M.; Rabaiah, S.; Schweimanns, N. Water resources in Jordan: A review of current challenges and future opportunities. *Water* **2023**, *15*, 3729. [\[CrossRef\]](#)
42. Aymen, A.T.; Al-husban, Y.; Farhan, I. Land suitability evaluation for agricultural use using GIS and remote sensing techniques: The case study in Ma'an Governorate, Jordan. *Egypt. J. Remote Sens. Space Sci.* **2021**, *24*, 109–117. [\[CrossRef\]](#)
43. Tamimi, A.H.; Gerba, C.P.; Hayek, B.; Choi, C.Y.; Freitas, R.J. Characterization of the quality of drying bed treated biosolids in Jordan. *J. Residuals Sci. Technol.* **2007**, *4*, 113–119.
44. Ministry of Water and Irrigation. *Jordan Water Sector National Master Plan*; Ministry of Water and Irrigation: Amman, Jordan, 2019.
45. International Union for Conservation of Nature. *Rangeland Restoration in Jordan: Restoring Vegetation Cover by Water Harvesting*; International Union for Conservation of Nature: Amman, Jordan, 2022.
46. Al-Bakri, J.T.; Salahat, M.; Suleiman, A.; Suifan, M.; Hamdan, M.R.; Khresat, S.; Kandakji, T. Impact of climate and land use changes on water and food security in Jordan: Implications for transcending “the tragedy of the commons”. *Sustainability* **2013**, *5*, 724–748. [\[CrossRef\]](#)
47. Hinsinger, P. Bioavailability of soil inorganic P in the rhizosphere as affected by root-induced chemical changes: A review. *Plant Soil* **2001**, *237*, 173–195. [\[CrossRef\]](#)
48. Kumar, R.; Vuppaladiyam, A.K.; Antunes, E.; Whelan, A.; Fearon, R.; Sheehan, M.; Reeves, L. Emerging contaminants in biosolids: Presence, fate and analytical techniques. *Emerg. Contam.* **2022**, *8*, 162–194. [\[CrossRef\]](#)
49. Saidan, M.N.; Al-Addous, M.; Al-Weshah, R.A.; Obada, I.; Alkasrawi, M.; Barbana, N. Wastewater reclamation in major Jordanian industries: A viable component of a circular economy. *Water* **2020**, *12*, 1276. [\[CrossRef\]](#)
50. AL-Hmoud, N.; Alrwashdeh, M.; Hayek, B. Assessing biosolids quality at the Mu'ta-Mazar wastewater treatment plant for the years 2016–2019. *J. Water Health* **2023**, *21*, 166–177. [\[CrossRef\]](#)

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.