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How Can Sewage Sludge Use in Sustainable Tunisian Agriculture Be Increased?

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Abstract: In recent years, farmers in Beja, an agricultural governorate in northwestern Tunisia, have expressed their willingness to use urban sewage sludge as agricultural fertilizer, especially with the unavailability of chemical fertilizers and the soil type of the region that is poor in organic matter. However, there is an imbalance between the important farmers' demand versus the limited quantity of sludge produced by the Beja wastewater treatment plants (WWTPs). In the face of this, this study aims to identify the problems related to the agricultural reuse of sludge in Beja and propose solutions to solve them. The quality of the sludge produced by the five Beja WWTPs was assessed based on physicochemical and microbiological parameters. The data were collected using the Delphi method, with 15 experts representing different positions on the issue treated. The SWOT-AHP methodology was used to define the strategies promoting the sustainable use and management of urban sewage sludge for sustainable agricultural development in Beja. Results showed that there were no problems with compliance with the Tunisian standards NT 106.20 for the sludge produced. A set of twelve practical conclusions was identified, constituting the strategies of Strengths–Opportunities, Strengths–Threats, Weaknesses–Opportunities, and Weaknesses–Threats deduced from the SWOT-AHP.

Keywords: agricultural reuse; Beja governorate of Tunisia; Delphi method; qualitative characterization; strategies identification; SWOT-AHP methodology; urban sewage sludge

1. Introduction

Efforts are being made throughout the world in terms of sanitation and wastewater treatment with the aim of saving water and protecting the environment. These efforts lead to the production of increasing quantities of secondary residues called "sludge" [1]. Globally, sewage sludge production is around 200 million tons per year [2]. Europe, North America, and East Asia are the main sewage sludge producers in the world [3]. The first two continents produce 40 million tons of dewatered sludge (DS) per year. Germany is the leading producer of sewage sludge in Europe, with 1.85 million tons in 2012 (about 21% of the total tonnage in Europe). The United Kingdom comes next with the production of 1.14 million tons of DS, followed by France with more than 1.043 million tons of DS [4,5]. Over the past few decades, the traditional ways of sewage sludge disposing, such as incineration and landfilling, have been strongly questioned because of their potential negative impacts on human health and the environment due to their polluting load. Discharging sludge into the sea, still practiced in the United States and Europe during the 1990s [6,7], was finally banned. The EEC also prohibited the discharge of untreated waste into all waterways from any system serving over 15 thousand people [8]. This has caused a renewed interest in recycling waste in agriculture, a practice known and adopted for several decades in all regions of the world [2,9,10].

Wastewater and its treatment produce by-products that contain major nutrients essential for plant growth and human food production, such as nitrogen (N), phosphorus (P), and potassium (K) [11,12]. Modern agriculture is reliant on the massive use of NPK fertilizers. The world demand for these nutrients increased annually by 1.4, 2.2, and 2.6%, respectively, in 2014–2018 [13]. Their production is based on the Haber-Bosch process, the extraction of phosphate rocks and wood ashes, respectively [10,14]. Their global application reflects unsustainable strategies with subsidized and inefficient uses. Indeed, P-fertilizers use, e.g., in food production, is inefficient as it has been stated in Europe that it takes 4 kg of reactive P to produce 1 kg of food with 40% of surplus remaining in the soil, and 50% loss of the system including 17% in water bodies. Chinese studies have indicated that it takes 13 kg of reactive P to produce 1 kg of food [15,16]. Additionally, phosphate rock, which is the main P source, is non-renewable and exhaustible within the next 50 to 130 years due to expected population growth [17]. Therefore, it is important to minimize the loss of P and convert it into a closed cycle [13]. P management strategies should be envisaged because there is no P substitute in agriculture, and in many places, especially the tropics, access to P still limits agricultural productivity [10]. In addition, prices of inorganic P-fertilizers are unstable, which may cause potential spikes in food prices [18]. To remedy this situation and to achieve effective sustainability of agricultural production, it is necessary to consider environmental, economic, and social aspects [3].

The use of sewage sludge as agricultural fertilizer provides a better alternative than landfilling and incineration [19]. Agricultural reuse of sludge is considered worldwide as a way to reduce environmental pollution and contribute to the circular economy by recapturing “waste” as a resource [20]. The sludge’s significant organic matter content (approximately 50% of its solid fraction) can improve physical, chemical, and biological soil characteristics and lead to improved agricultural yields when applied as a fertilizer [12,21]. Organic matter plays an important role in soil aggregation. It improves the soil porosity and raises water retention and movement [22]. The addition of organic matter promotes the soil substances’ decomposition and establishes a microbial equilibrium [13]. However, the main constraint is the safety of reusing sewage sludge because of the potentially concentrated harmful contents of metallic trace elements (MTEs), emergent pollutants, and pathogens [21,23].

In Tunisia, a developing North African country, the strategy relating to sludge management by 2035 aims to design solutions for its recovery, especially in the agricultural sector [24]. The low soil organic matter content [25] and the high organic manure price in the country [26] encourage the use of sewage sludge as an amendment. Before 1998, agricultural sludge use was significant and exceeded 60% of the volume produced. However, this was performed in an uncontrolled manner, which led to the prohibition of any further spreading [27]. With the elaboration of the NT-106.20 standard, sludge reuse has restarted modestly on pilot plots [28]. At present, only 3260 tons are recovered out of a total of 130,000 m^3/year of dried sludge through solar drying in beds from 123 wastewater treatment plants (WWTPs) in Tunisia [29],and despite the continuous increase in production, the amended areas with sludge remain insufficient, since the quantity of amended sludge did not exceed 18.6% of the quantity of dried sludge produced (2016) [30] and continued to decrease to 3% in 2020 [29]. In addition, the number of beneficiary farmers remains insufficient and has further decreased over the years [24,29–33].

Beja is among the leading Tunisian governorates in agricultural production. As agriculture is the region’s main economic activity, 91% of the land are dedicated to this sector [34]. During the 2019–2021 agricultural seasons and due to the unavailability of chemical fertilizers, such as ammonium nitrate and diammonium phosphate [35], seventeen farmers have expressed their interest in acquiring sludge from the regional services of the National Sanitation Utility (ONAS), and only fifteen of them received a part of the quantity requested [21]. Thus, the sludge demand by the Beja farmers is greater than the supply.

In view of the above, the theoretical objectives that this study aims to achieve are to identify the problems related to the sustainable agricultural reuse of sewage sludge in the governorate of Beja and propose solutions to solve them. These theoretical objectives lead to the practical objective of developing strategies that, based on the technical, socio-economic, environmental, and health aspects, promote the sustainable use and management of urban sewage sludge for sustainable agricultural development in Beja, a model that can be extrapolated to other regions of Tunisia and elsewhere.

2. Materials and Methods

2.1. Study Area, Sludge Sampling, and Analysis

The study area is the governorate of Beja located in Northwestern Tunisia and subdivided into 9 delegations (Figure 1). It had 306,600 inhabitants in 2017 on an area of 3740 km^2 [36]. There are five urban WWTPs in Beja located in the delegations of Beja-Nord, Medjez El Bab, Teboursouk, Testour, and Nefza, using the low load activated sludge process and drying beds for treatment of wastewater and sludge, respectively (Table 1). The dried sludge produced was from 49 to 540 m^3 per bed in 2020 [37]. Sludge sampling was carried out in 2018, 2019, and 2020 from all plants in the region at a frequency of one sample per month (a total of sixty sludge samples collected per year). A quantity of 1000 g of dry sludge was taken from the drying beds of each WWTP in hermetic plastic bags. The physicochemical characterization of the sewage sludge studied was based on the parameters given in Table 2.

Table 1. Main features of wastewater treatment plants of Beja governorate [37].

Plant	Delegation	Size in kg BOD_5/Day	Flow Rate (m^3/day)	Capacity E.I.	Wastewater Treatment Process	Sludge Treatment	Dried Sludge Production (m^3)
Beja-Nord	Beja	7800	14,000	144,000	Low load activated sludge (waterfall basins)	Drying beds	540
Medjez El Bab	Medjez El Bab	2000	4500	40,000	Low load activated sludge (waterfall basins)	Drying beds	500
Teboursouk	Teboursouk	719	1280	18,000	Low load activated sludge (oxidation ditch)	Drying beds	345
Testour	Testour	720	1180	19,000	Low load activated sludge (oxidation ditch)	Drying beds	256
Nefza	Nefza	680	1500	17,000	Low load activated sludge (oxidation ditch)	Drying beds	49

BOD_5:biochemical oxygen demand during 5 days. E.I.: Equivalent inhabitants.

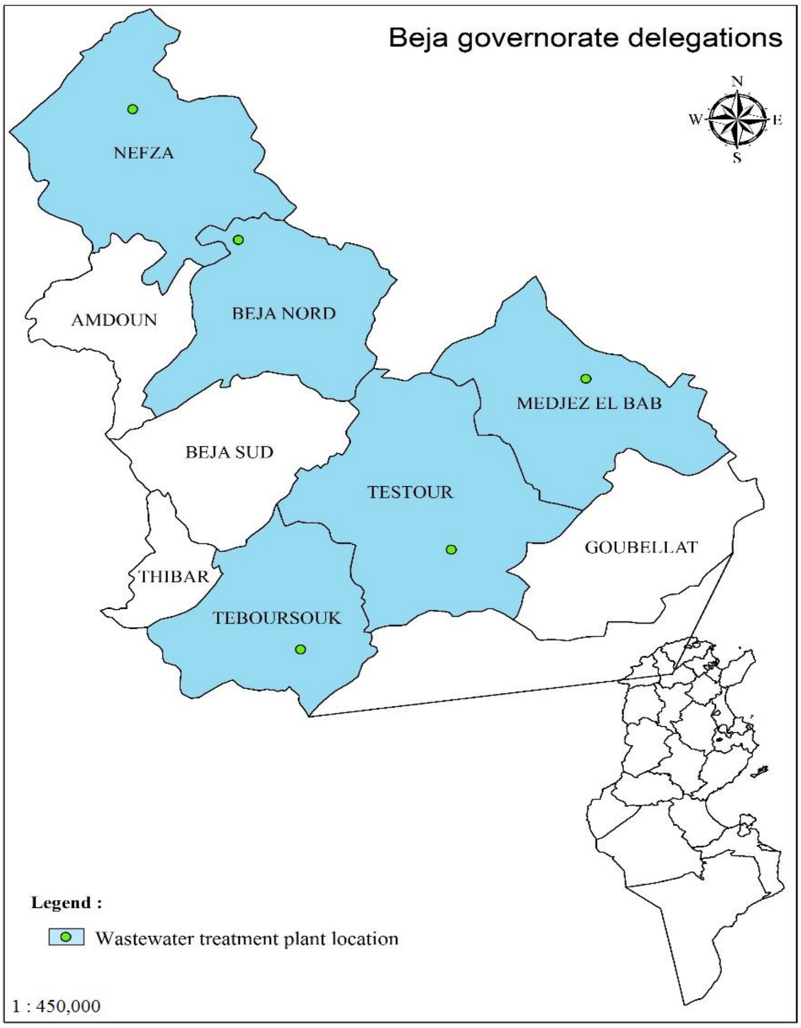

Figure 1. Location of wastewater treatment plants in Beja governorate, Northwestern Tunisia [38].

Table 2. Physicochemical parameters studied and analysis methods.

Parameter	Analysis Method	Unit	Source
pH	Electrochemical method	-	[39]
Dry matter (DM)	Gravimetry	%	[40]
Organic matter (OM)	Calcination	g/kg DM	[41]
Total organic carbon (TOC)	Colorimetry	g/kg DM	[42]
Total nitrogen (TN)	Titrimetric	g/kg DM	[43]
Total phosphorus (TP)		g/kg DM	
Cadmium		mg/kg DM	
Chromium		mg/kg DM	
Copper	Atomic emission-ICP	mg/kg DM	[44]
Mercury		mg/kg DM	
Lead		mg/kg DM	
Zinc		mg/kg DM	
Nickel		mg/kg DM	
Nematode eggs	Microscopic observation (arithmetic mean)	U/kg	-
Faecal coliforms	Solid/liquid extraction	UFC/kg	[45]

2.2. Collection of Information by the Delphi Method

The Delphi technique was used to collect information. The method relies on structuring a group of credible experts to deal with a complex issue [46], and through the consensus of their responses [47], inferences on subjective facts can be made. It starts with a delimitation of the problem, first questionnaire construction, and selection of experts [48]. As recommended by Skinner et al. [49], a panel of 15 experts representing different aspects regarding treatment and reuse of sludge was questioned with an initial bloc of 12 open questions relevant to economic, social, technical, environmental, and health dimensions (Table 3) followed the scheme presented in Figure 2. The selection of experts was based on the fact that (i) they are representative of the local people of Beja, who occupy or have occupied positions of interest in relation to our study subject within national bodies or organizations (Table 4); (ii) they are experts on wastewater treatment, operation of WWTPs, reuse of sludge, agricultural management and production, and social and rural economies; and (iii) the panel reflects a balance between women and men as shown in Table 4.

Table 3. Utilized Delphi questions based on economic, social, technical, environmental, and health dimensions.

Variable	Description	Source	Delphi Questions
Economic dimension	Evaluation of sewage sludge's impact on agricultural plant production was based on evaluation of crop productivity when fertilized with sludge, reduction of production costs due to less use of chemical fertilizers, and farmers' income.	[50–52]	1. Based on the Tunisian experience in agricultural effects of sludge, will the sludge amendment in agriculture improve crop productivity in the region of Beja? 2. Is it difficult to buy chemical fertilizers in the region? 3. Does the volatility of agricultural costs have a significant impact on farmers' income? 4. Does sludge use reduce production costs for farmers?
Social dimension	Assessment of the social impact of the agricultural reuse of sewage sludge includes assessment of health impact of sewage sludge use, farmer household income, sustainability of population and its environment, and rural exodus rate.	[20,52–54]	5. Do farmers follow national regulations regarding sludge use? 6. Have farmers in the region received training regarding safe sludge use, respecting environment and public health? 7. Does sludge contribute to sustainable farmer income and social security?
Technical dimension	Appropriate wastewater treatment produces sewage sludge that meets the recommended chemical and microbiological quality guidelines, at a low cost and with minimal operational and maintenance requirements. Correct operational treatment system activities provide desired sludge quality and quantity that meet regulated standards, while proper maintenance ensures efficient and sustainable operational objectives.	[55,56]	8. Do WWTPs in Beja governorate produce sewage sludge that meets the recommended chemical and microbiological quality guidelines? 9. Do maintenance activities at Beja governorate WWTPs ensure optimum functioning leading to sludge quality and quantity that meet national standards?
Environmental and health dimension	Assessment of environmental impacts of sewage sludge reuse in agriculture results in several agronomic benefits such as improved plant nutrients (nitrogen and phosphorus) that replace chemical soil nutrition. However, there are environmental and health issues including risk of soil contamination by organic and inorganic pollutants as well as pathogens, nutrient, and metallic trace element leaching, potentially toxic elements may be transferred via cultivated plants, possible contamination of groundwater, eutrophication of freshwater systems, impacts on soil biodiversity, and greenhouse gas emissions.	[10,53,57,58]	10. Is the quality of the sewage sludge produced by the various WWTPs in Beja complying to national regulations concerning reuse as organic soil amendment? 11. Is the reuse of sludge on the Beja soil beneficial for its quality and fertility aspects? 12. In Tunisia, cereal production is the agricultural product that consumes the most mineral nitrogen fertilizer. Beja is a cereal-growing area and among the regions that consume most of these fertilizers. Could the farm spreading of sludge replace the use of chemical fertilizers in the region?

Source: own elaboration.

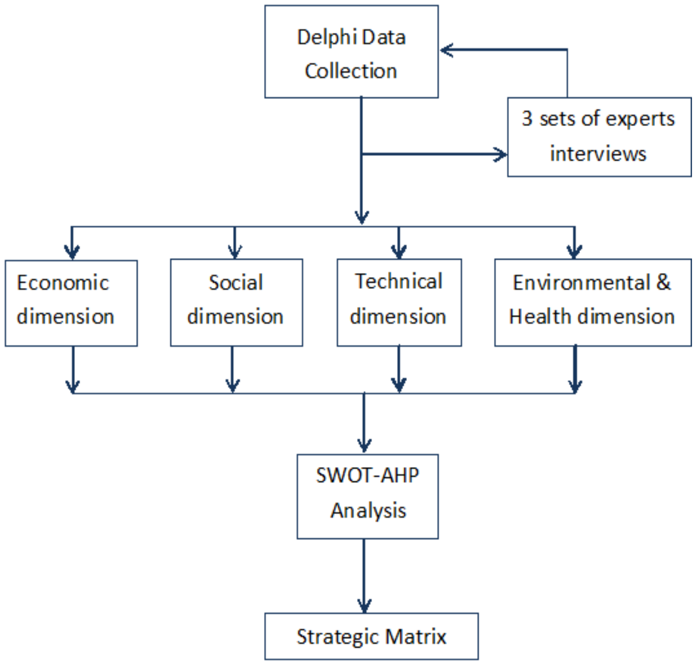

Figure 2. Flowchart of the research methodology used. The arrows represent the relationships between the methodological stages.

Table 4. Expert panel compliance.

Requirement	Condition	Number	Percentage
Sex	Women	8	53.3%
	Men	7	46.7%
Origin	Indigenous of Beja governorate	5	33.3%
	Non-Indigenous	10	66.7%
Residence	Beja governorate	7	46.7%
	Other Tunisian governorates	8	53.3%

Source: own elaboration.

Based on their responses, a second bloc of questions with 28 closed options was developed and presented to all participants. Then, a third questionnaire was sent to each expert (Figure 2), including the average score assigned by the group to each question as well as individual qualifications of each expert so that he/she could maintain or modify his/her answer.

2.3. SWOT-AHP Methodology

Assessment of the state-of-the-art of agricultural reuse of sewage sludge in the Beja region is based on the Strengths, Weaknesses, Opportunities, and Threats (SWOT) analysis matrix devised for strategic positioning and giving advice to implicated organizations such as the ONAS and the Regional Commissariat for Agricultural Development (CRDA). A conceptual framework was developed based on collected data to categorize the current situation into endogenous and exogenous factors. Endogenous factors are classified into strengths and weaknesses attributed to the organizations (ONAS and CRDA), while exogenous factors are classified into opportunities and threats attributed to the environment. However, as the SWOT analysis is a qualitative method not allowing direct strategical prioritization, it should be combined with another method, such as the analytical hierarchy process (AHP) that incorporates alternatives to make decisions based on multiple criteria [59]. The AHP considers qualitative and quantitative factors and leads to optimal solutions [60]. It follows a value measurement approach; the weight of each factor is obtained when comparing criteria pairs, which are subsequently given a score for their priority [48]. A comprehensive structure to combine intuitive and rational values is provided that verifies the consistency in decision making. By adopting the technique of Saaty [61], the reality perceived by the experts is transformed into a scale of reason determined through a peer-compared mathematical architecture. Thus, the best possible alternative or decision, facilitating strategic planning and decision making under multiple criteria, is found (Figure 2). The relevance of each factor is determined by comparing the alternatives two by two (A or B) and then evaluating them according to a significant scale (from 1 to 9) (Table 5). Finally, the internal consistency is assigned with the coefficient of reliability (Cronbach's alpha) [62].

Table 5. Importance scale for peer comparison of decisions based on criteria and sub-criteria [63].

Importance Scale	Definition	Description
1	Equally important	Two attributes contribute in the same degree to the goal
3	Moderately dominant	Experience/judgment favors some more attribute over another
5	Strongly dominant	Experience/judgment dynamically favors one attribute over another
7	Obviously dominant	A dominance of an attribute is demonstrated in practice
9	Extremely dominant	Evidence in favor of one attribute over another is asserted at the highest possible level
2, 4, 6, 8	Intermediate values	More subdivision or alternatives are required

The objectives and the methodology were explained to all experts participating in the Delphi and the SWOT-AHP stages before the beginning of the consultation rounds.

2.4. Strategy Matrix Definition

The strategic matrix was performed according to Weihrich's approach [64] and included four strategy groups emerging from crossing the results of external and internal factors in the SWOT analysis (Table 6): Weaknesses–Threats (WT), Weaknesses–Opportunities (WO), Strengths–Threats (ST), and Strengths–Opportunities (SO). It is a question of prioritizing the sub-factors that have become more relevant during the previous phase (SWOT analysis) by maximizing strengths and opportunities and minimizing weaknesses and threats.

Table 6. Matrix of strategies [64].

	Threats: T	Opportunities: O
Weaknesses: W	The strategies called "WT-Mini-mini" aim to minimize weaknesses and threats to reduce the risk that may exist.	The "WO-Mini-Maxi" strategies aim to minimize weaknesses and maximize opportunities to identify the internal weaknesses putting opportunities at risk.
Strengths: S	The "ST-maxi-mini" strategies aim to maximize the strengths that minimize the external threats.	The "SO-Maxi-maxi Strategies" aim to maximize the strengths allowing for exploitation or developing opportunities for the environment.

3. Results and Discussion

3.1. Sewage Sludge Quality in Beja

Results showed that the chemical and microbiological quality of the sewage sludge produced in all investigated WWTPs of the governorate of Beja is in accordance with the Tunisian standards NT 106.20 [65] (Table 7) for reuse in agriculture as a fertilizer. Beja sludge quality also complies with EU permissible limits of heavy metals in sludge for agriculture reuse, as well as in other Mediterranean countries such as Italy and France [66,67]. However, the zinc, cadmium, copper, and mercury contents exceed the limits applied in the Netherlands and chromium contents in Swedish legislation [68]. Typically, the use of sewage sludge is recommended to grow fodder and industrial crops. Food crops not in direct contact with the soil that are harvested at least 6 months later of application (e.g., wheat) may also be sludge fertilized [69]. Applying sludge to the soil in Beja, a cereal-growing region characterized by Mediterranean red soils, poor in organic matter, with a fine texture and calcareous accumulation [70], results in several benefits. These are providing valuable plant nutrients such as nitrogen and phosphorus, maintaining soil organic matter that plays a key role in strengthening soil structure and water-holding capacity [71], and stabilizing soil pH [21]. The fact that the sludge contains MTEs constitutes a disadvantage for agricultural use since an accumulation of these elements has negative consequences that can appear in the long-term depending on the physical and chemical conditions of the soil, especially in the case of uncontrolled application [72]. However, Ashraf et al. considered that the rational reuse of sludge contributes to the reduction of pollution risks because metal toxicity can be minimized by adding organic matter to the soil [73]. A proper balance ensuring appropriate sludge reuse, however, needs experimental investigations, including soil type, topography, and rainfall pattern [74,75], which can be assured by the agricultural research institutes in Tunisia. For example, Kchaou et al. [76] carried out a field experiment in the Beja area which made it possible to study the effect of the use of sludge on the growth, yield, and metal content of triticale (*X Triticosecale Wittmack*). They found that sludge application improved crop growth accumulated above-ground biomass and gave a significant part of the phosphorus, nitrogen, and other nutrient requirements of triticale crops. The biggest sludge rate used in this study (18 t/ha) increased straw yield by more than 123% compared to the control and about 57% compared to chemical fertilizer. In addition, sludge application did not increase the MTEs contents in the triticale crops.

Table 7. Characterization of urban sewage sludge from wastewater treatment plants (WWTPs) located in Beja governorate.

Parameter	Beja-Nord WWTP	Tboursok WWTP	Mjez El Bab WWTP	Nefza WWTP	Testour WWTP	NT 106.20 [65]
pH	7.35 ± 0.6	6.9 ± 0.5	6.9 ± 0.3	7.3 ± 0.5	6.8 ± 0.2	-
Dry matter (%)	80.8 ± 17.5	83.7 ± 22.0	90.4 ± 12.0	73.6 ± 25.3	88.5 ± 11.4	-
Organic matter (%)	58.6 ± 16.0	63.5 ± 4.5	53.3 ± 11.5	45.0 ± 15.6	49.0 ± 11.6	-
Total nitrogen (g/ kg DM)	25.5 ± 9.8	24.6 ± 19.5	26.1 ± 17.7	26.2 ± 11.3	18.6 ± 10.2	-
TOC (g/kg DM)	340.6 ± 95.3	373.3 ± 36.7	310.5 ± 68.0	228 ± 61.3	311 ± 68.0	-
Total phosphorus (g/kg DM)	13.8 ± 7.6	23.5 ± 5.0	23.6 ± 3.4	20.25 ± 10.0	21.35 ± 8.4	-
Cadmium (mg/kg DM)	0.57 ± 0.04	0.59 ± 0.02	1.3 ± 1.0	0.7 ± 0.3	0.62 ± 0.09	20
Chromium (mg/kg DM)	24.2 ± 16.8	22.2 ± 3.0	30.7 ± 11.4	105.5 ± 144.0	33.5 ± 15.7	500
Copper (mg/kg DM)	97.4 ± 32.0	101.7 ± 44.5	142.5 ± 55.5	162.3 ± 86.9	97.1 ± 66.0	1000
Mercury (mg/kg DM)	1.2 ± 0.01	0.4 ± 0.03	0.7 ± 0.02	0.75 ± 0.01	0.6 ± 0.02	10
Lead (mg/kg DM)	25.8 ± 11.6	17.65 ± 11.2	38.9 ± 35.0	59.8 ± 42.0	28.8 ± 15.2	500
Zinc (mg/kg DM)	267.3 ± 119.8	253.7 ± 93.4	331 ± 165.	795.7 ± 555.3	332.6 ± 117.2	2000
Nickel (mg/kg DM)	24.9 ± 10.5	13.2 ± 3.3	18.5 ± 7.7	25.7 ± 15.5	16.3 ± 9.0	200
Nematode eggs (HO/g DM)	$<1^{dl}$	$<1^{dl}$	$<1^{dl}$	$<1^{dl}$	$<1^{dl}$	-
Faecal coliforms (MPN/g DM)	$7{\cdot}10^5 \pm 10^7$	$3.3{\cdot}10^5 \pm 5{\cdot}10^5$	$4.4{\cdot}10^5 \pm 10^6$	$6.8{\cdot}10^5 \pm 9{\cdot}10^5$	$9.7{\cdot}10^5 \pm 10^5$	2×10^6

HO: helminth ova; ^{dl}: detection limit according to the United States Environmental Protection Agency (US EPA) [77] and World Health Organization [78].

3.2. The Delphi Method Application

For the analysis of the Delphi results, all expert answers were considered equivalent [79] without differentiating or weighing them. This follows Sackman [80], who confirmed the absence of a correlation between the experts' intelligence and the accuracy of their estimates. The first round of expert consultation with the first block of 12 open questions resulted in 83.3% of items meeting the consensus criteria, i.e., responses could be clustered in three continuous values with 75% of all panel responses [48]. However, the experts proposed questionnaire modifications. For this reason, the second block of 34 questions was reworked to better reach the objectives of the second round of consultations. This resulted in a consensus corresponding to 91.2% of all items and 81.6% of those initially proposed. Evaluation of the responses to the questionnaire was based on a central trend and dispersion measures of the set of answers for each item through the median and interquartile distances [81]. Table 8 shows the median, lower (Q1), and upper (Q3) quartiles in addition to the variation of relative interquartile calculated as the difference between Q3 and Q1. This iterative process determined values comprised between −0.25 and 0.25 in the relative interquartile variation between round one and round two [82]. The results displayed 89% of the total items consulted and 100% participation of experts in round two. Thus, it was decided that another round was not necessary [48].

Table 8. Consultation round results.

Question	Consensus	Median	Q1	Q3–Q1	Q3
Sludge agricultural spreading will improve crop productivity in the Beja region.	First round	7.00	6.00	1.00	7.00
Sludge spreading on the soils of Beja will improve production but should be applied according to soil type and following good agricultural practices.	Second round	6.50	6.00	1.00	7.00
Chemical fertilizers are unavailable in the region.	Second round	7.00	7.00	-	7.00
The volatility of agricultural input prices has a significant impact on the development of farmers' incomes.	Second round	6.50	5.25	1.75	6.50
Sludge use as an organic fertilizer has reduced production costs for farmers.	Second round	7.00	6.25	0.75	7.00
The farmers receiving sludge in Beja do the spreading in accordance with the sanitary practices recommended by the controlling national bodies.	First round	2.00	2.00	1.00	2.00
Farmers receiving sludge in Beja carries out the spreading in an uncontrolled manner.	Second round	5.00	2.75	3.00	5.75
The staff of CRDAs (Regional Commissariat for Agricultural Development) and CTVs (Territorial Extension Units) should be trained in good sludge spreading practices, with respect to the environment and public health.	Second round	7.00	7.00	-	7.00
Farmers in the region have been trained in good sludge spreading practices, respecting the environment and public health.	Second round	2.50	2.00	3.25	2.50
The CTV (Territorial Extension Unit) should assist farmers during spreading to ensure compliance with good practices.	Second round	7.00	6.25	0.75	7.00
The CRDA and/or the CTVs should periodically organize training workshops for farmers on good sludge spreading practices.	Second round	7.00	7.00	-	7.00
The use of sludge as organic fertilizers is positively correlated to the stability of farmers' income and thus promotes their social security.	First round	6.00	5.50	0.50	6.00
The wastewater treatment systems installed in Beja governorate are suitable to produce sewage sludge that meets the recommended chemical and microbiological quality guidelines.	First round	5.00	3.50	1.50	5.00
There are necessary maintenance activities to be carried out at the WWTPs of Beja governorate to ensure optimum functioning, with sludge quality and quantity meeting the standards.	First round	7.00	6.00	1.00	7.00
Sludge drying is satisfactory in the WWTPs concerned.	Second round	3.00	1.25	2.75	4.00
The quality of the sewage sludge produced by the various WWTPs in Beja complies with the standard, allowing its reuse as an organic soil amendment.	Second round	6.00	6.00	1.00	7.00
ONAS should increase the capacity of WWTPs in the Beja area.	First round	4.00	3.25	2.25	4.00
ONAS should ensure the proper functioning of WWTPs equipment.	Second round	6.50	6.00	1.00	7.00

Table 8. *Cont.*

Question	Consensus	Median	Q1	Q3–Q1	Q3
ONAS should ensure the proper functioning of the purification process.	Second round	6.50	6.00	1.00	7.00
ONAS should control industrial discharges upstream.	Second round	7.00	7.00	-	7.00
The WWTPs have sheds for the treatment and storage of sludge.	Second round	1.00	1.00	2.25	3.25
The state should provide sludge spreading and transport equipment for farmers.	Second round	7.00	6.25	0.75	7.00
The state should repair broken spreading and sludge transport equipment.	Second round	7.00	6.25	0.75	7.00
The frequency and quality of the analyses make it possible to make a definitive and solid judgment on the quality of the sludge.	Second round	7.00	4.00	3.00	7.00
The reuse of sludge on the Beja soil is beneficial for its quality and fertility aspects.	Second round	6.00	6.00	-	6.00
The sludge agricultural spreading has contaminated the soil of Beja.	First round	3.00	1.25	2.75	3.00
The sludge farm spreading could replace the use of chemical fertilizers by farmers in the Beja region.	Second round	6.00	6.00	-	6.00
Farmers in the region continue to use nitrogen fertilizers even when applying sludge spreading.	First round	5.00	2.00	4.50	6.50
State bodies should ensure periodic monitoring of soils that have received doses of sludge.	Second round	7.00	7.00	-	7.00
The state should draw up specifications that specify, explain, and define the conditions for using sludge as a fertilizer.	Second round	7.00	7.00	-	7.00
Farmers are warned about the potential risks of poor agricultural spreading practices on human and animal health and on agroecosystems.	Second round	6.00	2.25	4.50	6.00
The sludge quality is assessed on the basis of the available analyses and an additional campaign carried out as part of the green sector study.	Second round	4.00	1.75	3.00	4.00
The principles of traceability are applied to achieve food safety objectives for agricultural products originating from soils fertilized by sludge.	Second round	5.50	2.00	4.75	5.50

Source: own elaboration.

Agreements reached in the consultation (Table 9) relating to the identification of problems associated with the reuse of sewage sludge in agriculture in Beja included (I) positive effects of sludge application on soil quality and fertility, crop productivity, production cost reduction for farmers, in addition to income stability and improved social security. (II) The fact that sludge reuse could replace chemical fertilizers with volatile costs exerts a significant impact on the sustainability of farmers' income. (III) The need to train farmers in good sludge-spreading practices and warn about the risks of uncontrolled spreading on human and animal health and agroecosystems. (IV) The necessity to have a well-trained and well-prepared CRDA staff before organizing periodic training sessions for farmers and assisting them during spreading. (V) The wastewater treatment systems were able to produce sludge in accordance with the recommended national quality standards NT 106.20 [65]; however, there are necessary maintenance activities to be carried out by ONAS in the treatment plants of Beja to ensure adequate equipment and optimal operation of the treatment processes, in addition to controlling industrial discharge upstream and prepare sheds for the treatment and storage of sludge that should be analyzed frequently. (VI) The State bodies should provide new transport and sludge-spreading equipment for farmers, repair the existing ones, ensure periodic monitoring of the soils amended by the sludge, draw up specifications for using sludge in agriculture, and apply the traceability principles for food safety objectives of agricultural products grown on soils amended by sludge.

Table 9. Agreements attained through the Delphi consultation.

Final Delphi Question	Median	Q1	Q3–Q1	Q3	Interpretation
The sludge spreading will improve crop productivity and needs to be applied according to the soil type and with respect to good agricultural practices.	6.50	6.00	1.00	7.00	Strong agreement
The volatility of agricultural input prices and availability have a significant impact on the development of farmers' income.	6.50	5.25	1.75	7.00	Strong agreement
The use of sludge as an organic fertilizer reduces production costs for farmers.	7.00	6.25	0.75	7.00	Strong agreement
The sludge is spread in an uncontrolled manner without respecting health practices proposed by the controlling national bodies.	5.00	2.75	3.00	5.75	Moderate agreement
Farmers in the region have not been trained in good sludge-spreading practices to protect the environment and public health.	6.50	4.50	2.50	7.00	Moderate agreement
CRDA staff should be trained in good sludge spreading practices to protect the environment and public health.	7.00	7.00	-	7.00	Strong agreement
The CRDA should periodically organize training sessions for farmers on good sludge spreading practices and assist farmers during spreading to ensure compliance with good practices.	7.00	7.00	-	7.00	Strong agreement
Sludge reuse is positively correlated to the farmers' income stability and improve the social security.	6.00	5.50	0.50	6.00	Strong agreement
The wastewater treatment systems are suitable to produce sludge with the recommended chemical and microbiological quality standards.	5.00	3.50	1.50	5.00	Moderate agreement
There are necessary maintenance activities to be carried out at the WWTPs of Beja governorate to ensure optimum functioning, with sludge quality and quantity meeting the standards.	7.00	6.00	1.00	7.00	Strong agreement
ONAS should ensure proper operation of WWTPs equipment, ensure proper operation of the purification process and control upstream industrial discharge.	7.00	7.00	-	7.00	Strong agreement
WWTPs should have sheds allowing sludge treatment and storage.	7.00	7.00	-	7.00	Strong agreement
The quantities of sludge produced are not sufficient to meet the farmers' demands, nor to assure continued distribution during successive years.	7.00	7.00	-	7.00	Strong agreement
ONAS should consider bringing sludge produced in other governorates to meet the high demand in Beja.	7.00	7.00	-	7.00	Strong agreement
The state should provide new transport and sludge-spreading equipment for farmers in the region, and repair those that are broken.	7.00	6.25	0.75	7.00	Strong agreement
Analyses' frequency and quality allow for making a definitive and solid judgment on the sludge quality.	7.00	4.00	3.00	7.00	Strong agreement

Table 9. *Cont.*

Final Delphi Question	Median	Q1	Q3–Q1	Q3	Interpretation
Sludge spreading has improved the quality and fertility of Beja's soil.	6.00	6.00	-	6.00	Strong agreement
Agricultural sewage sludge reuse allows replacing the use of chemical fertilizers in the Beja region.	6.00	6.00	-	6.00	Strong agreement
The farmers in Beja continue to use nitrogen fertilizers, even when applying sludge spreading.	5.00	2.00	4.50	6.50	Moderate agreement
State bodies should ensure periodic monitoring of soils that have received doses of sludge.	7.00	7.00	-	7.00	Strong agreement
The state should draw up specifications that specify, explain, and define the conditions for using sludge as a fertilizer.	7.00	7.00	-	7.00	Strong agreement
Farmers are warned about the risks of poor agricultural spreading practices for human and animal health and agroecosystems.	6.00	2.25	4.50	6.75	Moderate agreement
Traceability principles are applied to achieve food safety objectives for agricultural products originating from soils fertilized by sludge.	5.50	2.00	4.75	6.75	Moderate agreement

Source: own elaboration.

The Delphi method presented the advantages of offering a strong involvement of the experts within the surveys carried out. As such, this method takes full advantage of the information and communication network concept [83]. The information collected is rich and abundant thanks to the confrontation and exploitation of divergent points of view. Anonymity guarantees independence of opinion, and the iterative process leads to a strong consensus [84]. However, the method has certain limitations, in particular, the length of the implementation due to the consequent number of round trips (3 or 4) and the availability of the experts. The time required (4 to 5 months) and the rigorous logistics (collection, circulation, feedback) of information are aggravating cost factors. Nevertheless, the uses of e-mail and discussion forums reduce expenses, make procedures more flexible, and speeds up the process [83]. The Delphi method also has the disadvantage that reaching consensus does not necessarily mean consistency [85]. It is advisable to arbitrarily determine a rule for validating the results of the interquartile intervals. Only opinions diverging from the median are considered and/or justified. This argument can, however, be weighted by the fact that atypical ideas are often richer in information than the norm. However, obtaining a consensus does not in any way guarantee the relevance of the prediction: a group of experts can consensually be wrong.

3.3. SWOT-AHP Method Application

The construction of the SWOT matrix, shown in Table 10, was based on the responses collected in the Delphi consultations and presented as Strengths (S), Weaknesses (W), Opportunities (O), and Threats (T), according to the economic, social, technical, environmental, and health analysis' dimensions of Table 3.

Table 10. SWOT matrix related to the state-of-the-art of agricultural reuse of sewage sludge in Beja.

Strengths (S)	Weakness (W)
S1: Sewage sludge is an organic fertilizer rich in macro- and micronutrients essential for agricultural production that can improve crop productivity. S2: Sewage sludge has a great capacity to improve the quality, structure, and water-holding capacity of the calcareous soils poor in organic matter that characterize the region of Beja. S3: Sewage sludge is produced continuously and in increasing quantity compared to chemical fertilizers that have varying availability in Tunisia. S4: Sewage sludge can replace the chemical fertilizers (ammonium nitrates and diammonium phosphate) used by the local farmers. S5: Sewage sludge is given free to farmers amid volatile chemical fertilizer prices in Tunisia, which reduces production costs and significantly improves the stability farmers' incomes. S6: Agricultural reuse of sludge will help stabilize farmers' incomes and promote social security.	W1: The demand for sludge by farmers in the Beja area is greater than the quantities made available by ONAS. W2: Farmers carry out the spreading in an uncontrolled manner that does not comply with the sanitary practices proposed by the national control bodies. W3: Farmers in the region of Beja are not trained in good practices (dosage, frequency of application, etc.) for safe sludge reuse. W4: There are no sludge storage sheds to preserve quality and avoid ignition and biological reactivation. W5: There is a problem with sludge transporting from the WWTPs to agricultural fields, as well as a lack of spreading equipment. W6: The distribution of sludge produced is not performed in a periodic way, even though for optimal agricultural production, the farmer must apply 6 t of sludge/ha for three successive years [28,65].
Opportunities (O)	**Threats (T)**
O1: Having wastewater treatment systems adapted to produce sludge that meets recommended quality standards, ONAS will increase the quantity of naturally dried sludge produced in Beja's WWTPs through the maintenance of equipment to ensure optimum functioning, e.g., improved drying beds can be obtained by changing the drainage layers composed of sand and gravel to avoid clogging of the drains, depending on the technical conditions of drying beds. O2: The ONAS program for the creation of sludge storage sheds, which is underway, allows to provide safe temporary storage of the sludge, improve its quality, and solve sludge management problems at the regional level. O3: The ONAS should provide safe transport to Beja from WWTPs in other regions with less demand for agricultural sludge reuse. O4: The CRDA should promote reliable control of sludge reuse through frequency and quality of analyses, assuring capacity building for farmers in sludge reuse through periodic training sessions on the application of good sanitary practices, and the safe reuse of sewage sludge. O5: The State could encourage farmers to reuse sludge as organic fertilizer by providing adequate equipment for transporting and spreading sludge in their fields.	T1: WWTPs can malfunction or fail when stressed beyond their historic design thresholds or functional condition. Consequential disruptions can lead to potentially serious implications for the environment and public health. T2: Climate change impacts sewage sludge quality: drought conditions and higher temperatures induce water usage restrictions, resulting in higher concentrated (higher number of contaminants) wastewater and sewage sludge, which are more likely to produce odor and have a negative impact on soil quality. T3: The absence of periodic monitoring of soils that have received doses of sludge could have harmful consequences due to the existence of heavy metals, pathogens, and organic pollutants in sewage sludge [86]. T4: The lack of specifications organizing the agricultural recovery of sewage sludge and limiting uncontrolled recovery such as continuing to use chemical fertilizers in the event of sludge spreading without preceding soil analyses. T5: The lack of traceability application of agricultural products coming from soil amended by sludge can impact the quality of food and thus jeopardize food safety.

Source: own elaboration.

3.3.1. Developing the Hierarchy of Decisions

We aimed to identify problems related to the agricultural reuse of sewage sludge in Beja and propose solutions that solve them. The hierarchical dependency between decision criteria and sub-criteria with strategic decisions was identified based on four levels (Figure 3). The first level is to identify strategies for improving conditions and propelling the agricultural reuse of urban sewage sludge in Beja. The second is the criteria of decisions, in this case, opportunities, threats, strengths, and weaknesses. The third level is comprised of sub-criteria of decisions in accordance with elements in the SWOT analysis outcome. Finally, the fourth level concerns the strategic decisions emanating from the SWOT analysis.

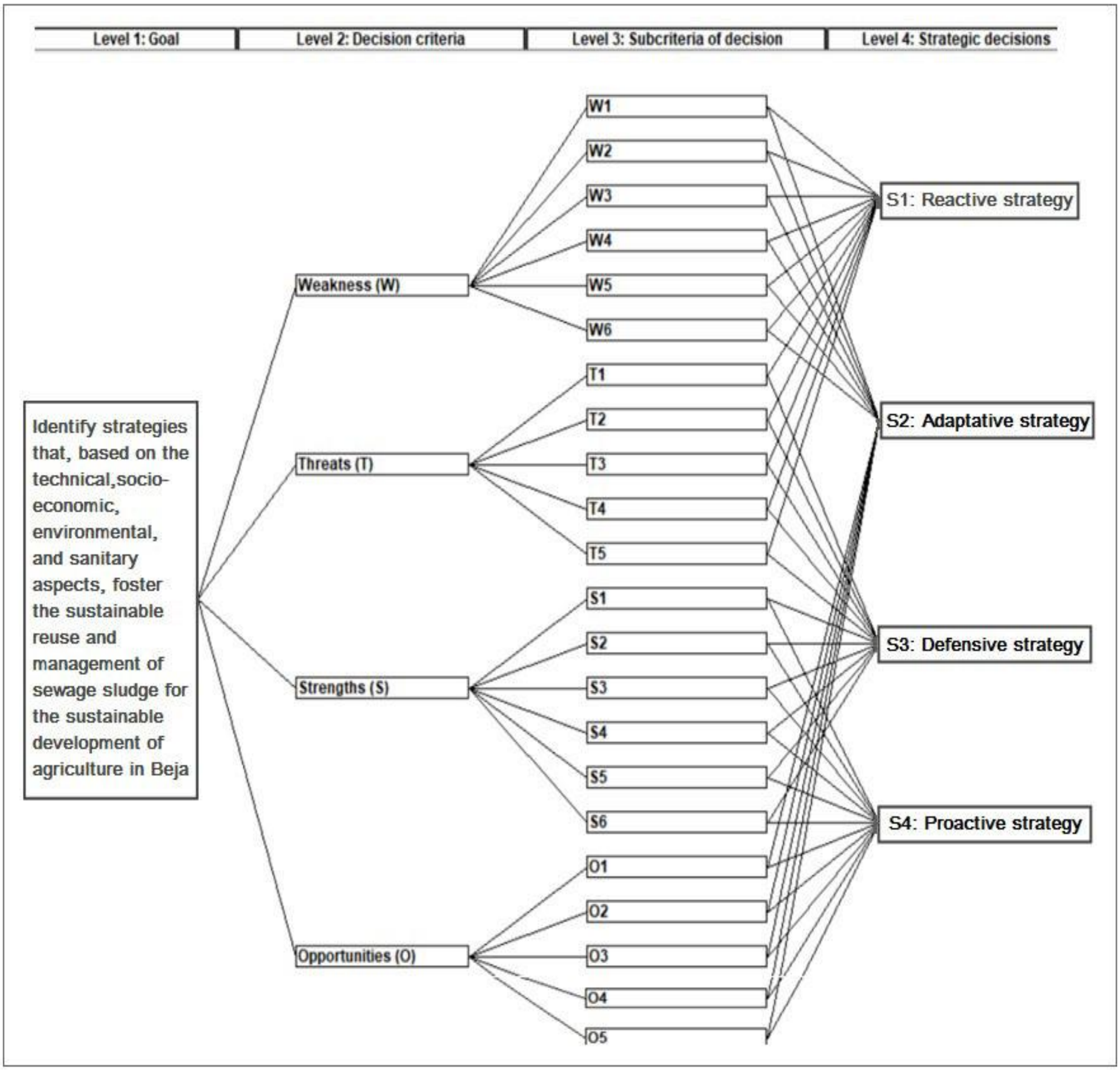

Figure 3. The hierarchical decision model for establishing the strategies to increase sludge use in agriculture.

3.3.2. Relevant Criteria and Sub-Criteria through the AHP Methodology

To assess the relevance of the criteria, another consultation of experts was launched, creating specific data necessary for the applied AHP method. The experts answered in a peer comparison SWOT structure, presenting relevant sub-criteria. The method does not involve direct contact and interaction between the experts, which avoids bias. Each expert was invited to supply a direct estimation of his or her approach, and all answers were processed mathematically. The algorithmic processing of the values proposed by the experts and the computation of each reliability coefficient (α) was carried out using the AHP Excel template with multiple inputs [87].

For the expert consultation, 15 invitations were sent to experts in the field of wastewater treatment and the operation of treatment equipment in WWTPs, as well as to academics and officials related to agricultural management, agricultural production, and social and rural economics. In total, seven responses gave results according to Table 11. To estimate the consistency of the consultation results, we calculated the reliability coefficient (α_T) to 0.743, which indicates adequate results [88,89] (Table 11).

Table 11. Relevance for all decision criteria and sub-criteria.

Criteria	Criteria Relevance at Level 2	Sub-Criteria	Sub-Criteria Assessment at Level 3		Rating Sub-Criteria Relative to the Total	
			Relevance	Ranking	Relevance	Ranking
Weaknesses (W)	21.2%	W1	33.7%	1	7.1%	19
		W2	19.7%	3	4.0%	11
		W3	19.8%	2	3.9%	10
		W4	8.2%	5	1.1%	3
		W5	7.5%	6	2.1%	5
		W6	11.1%	4	3.0%	7
Threats (T)	15.9%	T1	19.9%	3	2.9%	6
		T2	29.3%	1	8.1%	20
		T3	20.2%	2	3.1%	8
		T4	15.5%	4	0.8%	1
		T5	15.1%	5	1.1%	2
Strengths (S)	35.0%	S1	29.8%	1	8.7%	22
		S2	25.0%	2	7.1%	19
		S3	10.1%	5	5.2%	13
		S4	14.9%	3	6.0%	16
		S5	5.1%	6	1.9%	4
		S6	15.0%	4	6.1%	17
Opportunities (O)	27.9%	O1	30.0%	1	8.4%	21
		O2	15.4%	4	4.2%	12
		O3	14.8%	5	3.9%	9
		O4	19.9%	3	5.7%	15
		O5	19.9%	2	5.7%	14
Reliability coefficient relative to all criteria at level 2: α_2 = 0.62		Total reliability coefficient: α_T = 0.743				

Source: Own elaboration.

At level two, related to criteria assessment, the consulted experts considered that strengths (35.0%) and opportunities (27.9%) had a greater weight than weaknesses (21.2%) and threats (15.9%) when analyzing the state-of-the-art related to agricultural reuse of sewage sludge in the governorate of Beja (Table 11). In addition, at level three, concerning sub-criteria assessment, the experts highlighted the S1 indicating that sewage sludge is a fertilizer essential for agricultural production that can improve crop productivity and O1 concerning wastewater treatment systems adapted to produce sludge that meets quality standards. However, they call attention to W1 concerning the fact that the demand for sludge by farmers in Beja is greater than the quantities available, and T2 for the impact of climate change on sewage sludge quality. Indeed, the treatment, disposal, distribution, and reuse of wastewater and, therefore, sludge as by-products of wastewater treatment are subject to climate change effects through high energy costs and by increased volumes of wastewater entering treatment plants in areas subject to increases in rainfall, and by increased needs for reuse where droughts become more frequent [90]. The main processes affected by climate change in activated sludge WWTPs, such as those of Beja governorate (Table 1), are sedimentation, biological aeration of warm wastewater, processing of sludge, stabilization ponds, and chlorination [91].

3.4. Specification of Strategies

Four sets of strategies were deduced (Table 12) following the SWOT-AHP analysis, namely Strengths–Opportunities (SO), in-other-words maxi-maxi strategies, Strengths–

Threats (ST), i.e., maxi-mini strategies, Weaknesses–Opportunities (WO), i.e., mini-maxi strategies, and Weaknesses–Threats (WT), i.e., mini-mini strategies [63].

Table 12. Specified strategies.

Type	No.	Description
Strengths–Opportunities (maxi-maxi strategies): SO	SO1	Promote the agricultural reuse of sewage sludge as organic fertilizer rich in nutrients, which will improve crop productivity and quality, and which can be provided free of charge.
	SO2	Encourage farmers to reuse sludge by providing transport from WWTPs into fields and spreading equipment, which will result in improving the quality, structure, and water retention capacity of the calcareous soil low in organic matter that characterizes the Beja region.
	SO3	Bring sludge produced outside Beja where the demand for agricultural reuse is lower to ensure continuous sludge availability, and thus encourage farmers to use less chemical fertilizers that are difficult to buy in Tunisia.
Strengths–Threats (maxi-mini strategies): ST	ST1	Providing farmers with standard-compliant sewage sludge independently of climatic change conditions.
	ST2	Creating secure sheds for temporary storage that improves sludge quality and solve management issues at the regional level.
	ST3	Ensure periodic monitoring of the quality and structure of soils that have received sewage sludge.
Weaknesses–Opportunities (mini-maxi strategies): WO	WO1	Ensure regular and effective maintenance of wastewater treatment systems for an optimal operation to increase the quantities of sludge produced.
	WO2	Strengthen the capacities of farmers in the sludge safe reuse through periodic training on the application of good sanitary practices to encourage them to stick to this practice which contributes to stabilizing their income and promoting social security.
	WO3	Allow farmers to acquire sludge (6 t/ha) repeatedly for three years by increasing the quantities of sludge produced and ensuring safe temporary storage.
Weaknesses–Threats (mini-mini strategies): WT	WT1	Promote sustainable and secure sludge valorization by ensuring reliable control of the frequency and quality of product analyses, respecting the principles of traceability.
	WT2	Ensure regular, increasing, and meeting the standard sludge production while respecting historical design thresholds of the WWTPs.
	WT3	Create specifications organizing the agronomic recovery of sewage sludge and limiting any uncontrolled reuse.

Source: Own elaboration.

The criteria hierarchy results from the requirement to settle strategies based on reinforcing strengths (relevance: 35.0%) using opportunities (relevance: 27.9%); in particular, S1 (22nd), S2 (19th), S6 (17th), S4 (16th), S3 (13th) with opportunities O1 (21st), O5 (14th), O4 (15th), O2 (12th), O3 (9th); as well as those of turning W1 (19th), W3 (10th), and W2 (11th) into opportunities.

As indicated in Table 12, to reach the first hierarchy outcome, the strategy of the "SO" group was based on (I) promoting the reuse of sludge as organic fertilizer rich in nutrients, (II) providing equipment for sludge transport and spreading to farmers, and (III) bringing sludge produced in other regions where the demand for agricultural reuse is lower. Concerning the "ST" group, the strategy consisted of (I) providing farmers with standard-compliant sewage sludge independent of climatic change conditions, (II) creating secure sludge sheds for temporary storage, and (III) ensuring periodic monitoring of the quality and structure of soils amended by sewage sludge since sludge spreading on soil tends to increase MTEs accumulated in the soil [27]. However, several studies have shown that a significant accumulation of MTEs occurs mainly in the soil surface (0–10 cm depth) [92–94], and leaching is unlikely, provided a high soil organic content [27,95].

For the "WO" group, the strategy was (I) ensuring regular and effective maintenance of wastewater treatment systems, (II) strengthening the capacities of farmers for safe sludge reuse through periodic training on good sanitary practices, and (III) allowing farmers to acquire sludge, at the dose of 6 t/ha, repeatedly for three years [28,66]. Studies in Tunisia and elsewhere have shown that the cumulative effect resulting from the periodic addition of sludge over two or three consecutive years generates better impacts on the growth and production of crops and the quality of the soil than single applications [96–99]. About 18 t/ha divided over three years (6 + 6 + 6 t/ha) is considered efficient to meet the major nutrient needs for growth and to achieve optimal yields without having to resort to additional fertilizing [28,97].

Finally, the strategy of the "WT" group was (I) ensuring reliable control of the frequency and quality of product analyses, respecting the principles of traceability, (II) respecting the historical design thresholds of the WWTPs to produce sludge meeting the standards, and (III) create specifications regarding organizing agronomic recovery of sludge and encouraging farmers to respect the main limitations for agricultural sludge use, which are [65,99,100]:

- Do not use sludge on agricultural land where vegetables and eaten-raw fruits grow,
- The sludge can be used after 8 months of natural drying,
- Grazing on land treated with sludge should not be permitted until two months after its application,
- Use mechanical burial methods for sludge and not traditional manual methods,
- Sludge produced should not be stored near drainage and irrigation canals and water resources,
- Reduce the number of displacements of sludge so that the agitation of dust in the air is reduced to a minimum,
- Limit the application of the amount of sludge rich in heavy metals,
- During the 30 days following the application of sludge, limit access to agricultural land where it has been applied,
- Application is limited to areas with a 5% slope and no application near water supply plants, areas where the water table is 1 m deep, less than 150 m from a well, and less than 750 m from an intake surface water used for food,
- The sludge should undergo pathogen-reducing treatment (thermophilic process, composting, or humification) before any agricultural reuse.

4. Conclusions

Due to the unavailability of chemical fertilizers during the period 2019–2021, farmers in Beja, one of the most important agricultural production areas in Tunisia, have expressed a great interest in reusing sewage sludge as an organic amendment in their fields. However, the application of sludge in agriculture needs to be regulated and controlled. Analysis of the chemical and microbiological quality of sludge produced by the five treatment plants located in Beja has shown that they comply with Tunisian standards NT 106.20 in terms of the content of metallic trace elements (cadmium, chromium, copper, mercury, lead, zinc, and nickel) and microorganisms (nematodes and fecal coliforms). This sludge can therefore be reused as organic fertilizer for fodder, industrial crops, and food crops with no contact with the soil that are harvested at least 6 months after sludge application. Sludge reuse for vegetables and direct eaten fruit is not recommended to avoid all health risks due to possible contamination by microorganisms.

To identify problems related to the sustainable agricultural reuse of sludge in Beja, investigations using the Delphi methodology with experts from different areas were performed to obtain information to feed a SWOT matrix. Strategies promoting sustainable use and management of urban sewage sludge for sustainable agricultural development in Beja were defined based on the SWOT-AHP methodology, which allowed to identify of practical conclusions summarized into three "SO" strategies of promoting the sludge reuse as organic fertilizer rich in nutrients (SO1), providing equipment for sludge transport and spreading to farmers (SO2), and bringing sludge produced in other regions where the demand for agricultural reuse is lower (SO3). Three "ST" strategies were identified, including the provision of farmers with standard-compliant sewage sludge independently of climatic change conditions (ST1), creating sludge-secure sheds for temporary storage (ST2), and ensuring periodic monitoring of the quality and structure of soils fertilized by sewage sludge (ST3). The three "WO" strategies recognized were ensuring regular and effective maintenance of wastewater treatment systems (WO1), strengthening the capacities of farmers for safe reuse of sludge through periodic training on the application of good sanitary practices (WO2), and allowing farmers to acquire sludge (6 t/ha) repeatedly for three years (WO3). In addition, the three "WT" strategies aimed to ensure reliable control of the frequency and quality of product analyses, respecting the principles of traceability (WT1), respecting the historical design thresholds of the WWTPs to produce sludge meeting the standards (WT2), and creating specifications regarding the agronomic value of sludge and limiting any uncontrolled reuse (WT3). Based on technical, socio-economic, environmental, and health aspects, these strategies promote sustainable use and management of urban sewage sludge for sustainable agricultural development in Beja. These results can be extrapolated to other Tunisian regions, and to other MENA countries, with similar climatic, soil, and socio-economic conditions.

This research was based on expert criteria, and it omitted, for design reasons, the vision of the population and particularly that of the farmers, knowing that the expert criterion risks can be affected by a particular interest or a personal experience. Thus, future lines of research should consider experiences drawn directly from farmers, individuals, and populations.

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