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Innovation in the Management of Sludge Generated in Domestic Waste Water Treatment Plants in Perù

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Abstract In the 7 domestic wastewater treatment plants -PTAR- evaluated, 81630.72 m^3 / day of wastewater are treated and 2537.85 Tn / day of sludge with high moisture content are generated, becoming a problem since the spaces for their confinement are scarce and / or that the existing distances from the generation centers to the final disposal sites are significant. The sludge was characterized physically-chemically and biologically on two occasions and compared with the maximum permissible limits established in the Peruvian, Mexican and EPA regulations, then the results showed excess concentrations of Cadmium, Zinc and Thermotolerant Coliforms, for which prior treatment is recommended. Nutritional concentrations of the generated sludge were also determined, comparing the results with the quality of the compost that is made at the Pampamarca Chico-Carhuaz Plant, which is concluded that they have high concentrations of Total Nitrogen, Organic Matter and acceptable pH; there is a demand for its use to fertilize agricultural land. The conversion of sludge waste to input requires innovation in management, and currently only one company is hired that is in charge of storing, transferring and disposing of them in sanitary landfills. Treating crude sludge, enriching it and marketing it obviously requires a change in management in order to generate business opportunities, already converted into an input, within the framework of the Circular Economy.

Keywords Waste Water Treatment Plants, Crude Sludge, Fertilizers, Energy Valuation, Circular Economy

1. Introduction

1.1. Problem Description

Currently, in Peru, 164 out of 253 localities managed by the sanitation service provider companies (EPS) partially or fully treat the wastewater collected through sanitary sewer systems in wastewater treatment plants (WWTPs) [1], [2], [3]. This corresponds to coverage for approximately 14,083,000 inhabitants, who generate a volume of 2,293,000 m^3/day of wastewater.

The wastewater treatment process removes various contaminants, including solid waste, sand, foam, and residual sludge. The sludge generated, particularly primary sludge, often contains debris that must be removed to prevent damage to treatment plant equipment. For this purpose, the implementation of pre-treatment units, such as screens or grinders, is essential.

According to [4],[5], before final disposal or beneficial use, residual sludge must be stabilized to reduce vector attraction, minimize odor generation, and decrease health risks. Additionally, sludge must undergo dewatering processes to reduce its volume and facilitate handling [6], [7].

Stabilization of waste sludge allows reducing its mass and volume, facilitating dewatering and reducing pathogenic organisms, odors, and vector attraction are significant concerns, but the most critical challenge is the high investment and operational costs [8]. Anaerobic digestion offers the greatest advantages; however, its construction costs are higher, as digesters require a large number of peripheral equipment, the residual sludge must be heated, and the water in the sludge contains high ammonia concentrations, which can lead to process instability if not properly controlled. Although aerobic digestion has lower construction costs than anaerobic digestion, its operational costs are higher due to the need for continuous air supply to stabilize the sludge [9], [10]. Composting is labor-intensive and can generate strong odors. Additionally, it may increase the total biosolids mass for disposal and pose a risk of pathogen transmission through airborne dust [11], [12]. The construction of an internal sanitary landfill (ISL) presents a major challenge as it requires a large land area, and selecting a suitable site that meets legal and regulatory requirements is complex. These landfills have a limited lifespan, after which they become saturated, requiring the identification of a new site since expanding the existing one is not always feasible. Furthermore, obtaining the necessary environmental permits is essential [13], [14].

If an internal sanitary landfill (ISL) is available, the management and treatment of leachates also become a challenge, as they tend to accumulate within a few months of the year. In addition to disposal site concerns, wastewater treatment plants (WWTPs) must have a designated container for storing residual sludge. This storage process can pose several safety risks, as highlighted in [15], [16]; at high temperatures, sludge can self-heat and ignite, and under certain conditions, dry solid particles or dust may even cause explosions.

The 2015 report commissioned by the National Superintendency of Sanitation Services (SUNASS), titled Diagnosis of Wastewater Treatment Plants in the Operational Scope of Sanitation Service Provider Companies, identifies key challenges in residual sludge management [17], [18], [19], [20].

Regarding the regulatory framework, the main issues include the lack of authorized sites for the final disposal of residual sludge and solid waste from WWTPs, as well as the absence of regulations governing sludge management for agricultural reuse. From an operational and maintenance perspective, major concerns include the lack of sludge removal in 50% of stabilization pond-type WWTPs and insufficient financial resources for proper operation and maintenance [21], [22], [23].

It is worth noting that SEDAPAL is the only company that ensures the proper disposal of residual sludge in sanitary landfills. In its seven wastewater treatment plants (WWTPs), sludge management is carried out by a contracted solid waste operator through the following procedure: storage and drying using solar radiation, facilitated by metal containers, and transport and final disposal in sanitary landfills, using appropriate vehicles.

Sludge management in the WWTPs of Metropolitan Lima varies depending on the treatment process and final disposal method. At PTAR Ancón, vermiculture with Eisenia foetida is used to stabilize sludge and produce humus, which is then applied in green areas. PTAR Cieneguilla and PTAR José Gálvez generate sludge with low heavy metal concentrations and acceptable biological levels, making them suitable for soil recovery and reforestation. At PTAR Huáscar, while metal concentrations remain within permitted limits, thermotolerant coliforms exceed regulatory standards, necessitating ozone treatment to reduce the pathogen load. PTAR Julio C. Tello shows inconsistent cadmium concentrations, requiring additional monitoring to assess its viability for reuse. Meanwhile, PTAR San Juan de Miraflores and PTAR Ventanilla, originally designed for 160 L/s but currently overloaded, lack updated information on their sludge management practices.

1.2. Regulatory Framework

- To determine the quality of residual sludge, the results of the sample analyses were compared against the following standards:
- Mexican Official Standard NOM-004-SEMARNAT-2002: Environmental Protection – Residual Sludge and Biosolids. Specifications and Maximum Permissible Limits of Contaminants for Their Utilization and Final Disposal.
- EPA Standard 40CFR-503 PC-EQ QUALITY.
- Peruvian Standard D.S. Nº 015-2017-VIVIENDA: Regulation for the Reuse of Residual Sludge Generated in Wastewater Treatment Plants.

Table 1 lists the Maximum Permissible Limits (MPL) established by each standard.

The Peruvian Standard, DS No. 015-2017-VIVIENDA, considers 2 classes of residual sludge, Class A: those applicable to the soil without sanitary restrictions[24], [25]; Class B: those applicable to the soil with sanitary restrictions according to the location of the soils and/or type of crops. The maximum permissible limits can be seen in Table 1. It should be noted that the Mexican Official Standard NOM-004-SEMARNAT-2002, considers 3 classes of residual sludge quality and for each of them establishes maximum permissible limits, which are shown in Table 2.

Each class corresponds to a specific type of sludge treatment. As has been pointed out, in Peru sludge treatment is incipient or non-existent, so in the case of the Mexican Standard, the limits contained in the lowest category have been selected, which corresponds to C. Likewise, to determine the type of use of Biosolids, sludge with up to 85% moisture content [26], [27], [28], the detail is specified in Table 3.

Table 1. Maximum Permissible Limits for biosolids

PHYSICAL CHEMICAL PARAMETERS	UNIT	MEXICAN STANDARD		EPA STANDARD	D.S. No. 015-2017-HOUSING
		Excellent	Well		
Arsenic	mg/Kg	41	75	41	40
Cadmium	mg/Kg	39	85	39	40
Chromium	mg/Kg	1200	3000	Unregulated	1200
Copper	mg/Kg	1500	4300	1500	1500
Mercury	mg/Kg	17	57	17	17
Molybdenum	mg/Kg	--	-	-	-
Nickel	mg/Kg	420	420	420	400
Lead	mg/Kg	300	840	300	400
Selenium	mg/Kg	--	-	100	-
Zinc	mg/Kg	2800	7500	2800	2400
MICROBIOLOGICAL PARAMETERS	**UNIT**	**MEXICAN STANDARD**		**EPA STANDARD**	**D.S. No. 015-2017-HOUSING**
Total Coliforms (35 ℃)	MPN/g	-		-	-
Thermotolerant Coliforms (44.5 ℃)	NMP/100g	2 000 000		<2,000,000 Class B <1000 Class A	-
Helminth eggs	Eggs/g	< 35		>1 Class B <1 Class A	<1/4g ST Class A
Protozoan Cysts	Cysts/g	-		-	-
Salmonella	MPN/g	< 300		-	<1NMP/10g ST Class A
Cryptosporidiumsp	No. of cysts/mg	-		-	-

Source: Own elaboration

Table 2. Maximum Permissible Limits for Pathogens and Parasites in Sludge and Biosolids

CLASS	Bacteriological Indicator of Contamination	Pathogens	Parasites
	Fecal coliforms NMP/g on a dry basis	Salmonella spp. NMP/g on a dry basis	Helminth eggs/g on a dry basis
To	Under 1000	Under 3	Under 1(a)
B	Under 1000	Under 3	Under 10
C	Less than 2000000	Under 300	Under 35

(a) Viable helminth eggs

MPN: most probable number

Source: Mexican Official Standard NOM-004-SEMARNAT-2002

Table 3. Biosolids Utilization

GUY	CLASS	USE
Excellent	To	• Urban uses, without direct public contact during its application. • Those established for class B and C.
Excellent or Good	B	• Urban uses, without direct public contact during its application. • Those established for class C.
Excellent or Good	C	• Forest Uses. • Soil Improvements. • Agricultural Uses.

Source: Official Mexican Standard NOM-004-SEMARNAT-2002

Regarding the EPA Standard 40CFR-503 PC-EQ QUALITY, the classes correspond to the following uses:

Table 4. Biosolids Exploitation

CLASS	USE
To	• They can be used without any restriction (direct consumption).
B	• Soil recovery. • Forest plantations. • Non-direct consumption. • Landfill coverage.

Source: regulations EPA 40CFR-503 PC-EQ QUALITY.

Table 4, based on EPA Standard 40CFR-503 PC-EQ QUALITY, classifies biosolids into Class A and Class B according to their treatment level and potential uses. Class A biosolids can be used without restrictions, including for direct consumption, as they have undergone treatment to eliminate pathogens and contaminants to safe levels. In contrast, Class B biosolids have restrictions and may only be used for soil recovery, forestry plantations, non-direct consumption crops (such as those not intended for immediate human consumption), and sanitary landfill cover, as they require stricter controls to prevent health and environmental risks.

1.3. Objectives

1.3.1. General

To develop innovation in the management of sludge generated in domestic wastewater treatment plants in Lima, Peru.

1.3.2. Specific

- To determine that management innovation allows conversion into an input by improving the quality of the sludge generated in domestic wastewater treatment plants in Lima, Peru.
- To relate the contribution of innovation in management to what contributes to commercialization by acquiring commercial value the sludge generated in domestic wastewater treatment plants in Lima-Peru.

The following table notes some characteristics of the selected sample.

Table 5. Samples of the research work

number	SYSTEM NAME	DISCHARGE POINT	SIZE (Tn/year)
1	San Juan WWTP	Dumping into the sea Reuse	2 440,00
2	Julio C. Tello WWTP	Discharge into the Lurín River Reuse	806,12
3	Cieneguilla WWTP	Discharge into the Lurín River Reuse	87,69
4	Ancon WWTP	Dumping into the sea	236,29
5	Ventanilla WWTP	Dumping into the sea Reuse	7 499,70
6	Huáscar WWTP	Reuse	180,22
7	José Gálvez WWTP	Reuse	187,00

Source: Own elaboration.

2. Materials and Methods

2.1. Pre-Field

The processes and operations carried out in the sample WWTPs were noted, identifying the procedures that promote the generation of sludge, the management and results obtained. Interviews were conducted with people with knowledge of the subject, in order to gain knowledge about sludge management. Since the use of this sludge for agricultural purposes was established, a survey sheet was designed that was applied to people interested, or potentially interested, in such use. A file was also designed that made it possible to establish the usefulness of the sludge for energy generation purposes [29],[30],[31].

2.2. Fieldwork

Samples of the raw sludge were taken in order to establish its physical, chemical, biological and nutritional characteristics, for which the following methodology was followed:

2.2.1. Materials

- Containers and/or pipettes
- Zip-top plastic bags approx. 100 ml
- Vinyl gloves and face mask
- Labels and thin marker with indelible ink
- Sterilized glass bottles, with a wide neck and a capacity of 500 to 1000 gr
- Survey Cards

2.2.2. Sample Types

Method of Sampling and Preparation

Samples of dry sludge shall be taken considering the following:

- Homogenization of samples, using suitable containers and/or pipettes, partial samples of different sludge ages were collected. They were properly mixed in order to obtain a homogeneous mixture.
- When the samples were taken in different places, variable amounts of 5 kg to 10 kg were considered, and at the time of homogenization one of at least 5 kg was selected.
- The selected samples were placed in suitably sealed plastic bags, preventing them from heating up as much as possible.
- The basic data were recorded: date and place of sampling, and sent to the laboratory for analysis.
- The samples were kept refrigerated at 4ºC until analysis.

Sludge sampling, in each WWTP, was carried out on the dates and locations detailed in Table 6.

Table 6. Sludge sampling points

Monitoring Date	Sampling Point	Description	UTM coordinates WGS84	
			This	North
ANCON WWTP:				
May 26, 2015 January 11, 2019	PL-A-01	Lagoons	263782.43	8699533.25
CIENEGUILLA WWTP:				
May 21, 22, 2015 February 1, 2019	PL-C-01	Sludge drying bed	301484	8658381
HUASCAR WWTP:				
27 October 2015 March 15, 2019	PL-H-01	Sludge drying bed	290101	8646712
JOSÉ GÁLVEZ WWTP:				
07 September 2015 April 20, 2019	PL-G-01	Sedimentation Lagoon	292853	8647489
JULIO C. TELLO WWTP:				
May 21, 2015 February 8, 2019	PL-J-01	Sludge drying bed	293847.13	8643993.22
SAINT JOHN WWTP:				
May 27, 2015 June 7, 2019	PL-S-01	Sludge drying bed No. 2	285572.40	8652350.82
VENTANILL WWTP:				
November 7, 2015 January 11, 2019	PL-V-01	WWTP Lagoon No. 5	266311.72	8687621.00

Source: Own elaboration (field data)

Table 7. Methods of Analysis of Sludge Samples

Parameter	Method of Analysis	Specification
Total solids	SM-2540 B	Drying at 105 ℃ ± 5 ℃
Volatile solids	SM-2540 E	Calcination at 550 ℃
pH	SW-9045	Suspension and potentiometric determination
Electrical conductivity	SW-9050	Conductivity Determination
Organic matter		Calcination at 550 ℃
Al, Ag, As, Ba, Be, Cd, Co, Cr, Cu, Fe, Mn, Mo, Ni, Pb, Sb, Se and Sn, Bi, Hg, N, P, K	EPA 6010	Graphite or electrothermal furnace technology
Thermotolerant Coliforms	Standard Methods 9221 A, 1995	Tube dilution counting method
Salmonella spp.	Standard Methods 9260 D, 1992	
Helminth Eggs	NOM-AA-113-SECOFI-1999	

Source: Own elaboration

Laboratory Analysis Methods

The analysis methods established by the Environmental Protection Agency (EPA) were applied, as detailed in Table 7.

In order to determine its potential as a product, following the same method of sampling and analysis, the concentration determination of the following parameters was carried out: Total Nitrogen, Phosphorus, Potassium, pH and Organic Matter.

100 survey cards were applied to each family in order to establish the potential for using the sludge for agricultural purposes, as well as 9 survey cards (8 cement plants and 2 brick factories) to measure the need to use the sludge for energy generation purposes.

In Table 7, volatile solids and organic matter are related but not equivalent. Volatile solids provide an estimate of the organic matter content in sludge or biosolids, as they decompose at high temperatures during the calcination process. Since organic matter serves as a substrate that promotes microbial growth and the proliferation of harmful fauna, regulations such as NOM-004-SEMARNAT-2002 establish criteria for volatile solids reduction to ensure proper treatment and minimize health and environmental risks.

2.3. Post-Field

The physical, chemical and bacteriological results obtained from the laboratory analysis were systematized, graphed and compared with the maximum permissible limits of the Peruvian, Mexican and EPA standards. The results of the nutritional concentrations of the sludge were compared with the concentrations obtained from one of the high-quality composts obtained in Peru, and obtained from the Carhuaz landfill (Huaraz). Finally, the corresponding results, conclusions and recommendations were discussed, also considering the results obtained from the surveys applied both to measure agricultural and energy uses of raw sludge.

3. Results

3.1. WWTP Operational Indicators

Table 8 and table 9 summarize the results, according to the importance of the research work, and which allowed us to discuss the results more precisely.

3.2. Quality of Raw Sludge

Table 10 summarizes the sludge quality evaluation of the 7 WWTPs.

3.3. Commercial Quality of Sludge

a. Use as a fertilizer

To determine the nutritional potential of raw residual sludge, its characteristics were analyzed. The results are presented in Table 11, which also highlights that the low organic matter content in some sludge samples can be attributed to various treatment processes. Among these, aerobic or anaerobic digestion plays a key role, as microbial activity decomposes organic matter, reducing its concentration. Additionally, chemical stabilization processes, such as lime treatment or advanced oxidation, can further degrade organic compounds. Another influencing factor is sludge age, as prolonged retention times in digesters or stabilization ponds promote the mineralization of organic matter. Finally, sludge dewatering and drying reduce its organic content by eliminating volatile components.

In order to determine the nutritional potential of the raw sludge, the results of this characterization were compared with the content of the Carhuaz compost. See Table 12.

b. Energy value

Table 13 shows the results obtained for the calorific value of the dry sludge from the San Juan and Ventanilla WWTPs.

Table 8. Flows, treatments, sludge production and sludge/water ratio

WWTP	Operating Flow		Type of WWTP Treatment	Type Sludge Treatment	Sludge Production		Sludge/Water Ratio (%)
	(l/sec)	(m^3/year)			(Tn/year)	(m^3/year)*	
Ancon	40,51	1 277 523,36	LF	D	236,26	229,38	0.018
Cieneguilla	68,41	2 157 377,76	THE	LS	87,89	85,33	0.004
Julio C. Tello	21,19	668 247,84	AA	LS	806,12	782,64	0.117
San Juan	355,50	11 211 048,00	Lai	LS	917 318,00	890 600,00	7.944
José Gálvez	100,45	3 167 791,20	AA	LS	187,00	181,55	0.006
Huáscar	88,24	2 782 736,64	AA	LS	180,22	174,97	0.006
Ventanilla	270,50	8 530 488,00	AA	D	7 499,70	7 281,26	0.085
TOTAL	944,90	29 795 212,80			926 315,19	899 335,13	

Notes: LF = optional gaps; LA = activated sludge; AA = Anaerobic-Aerated; LAi = Aerated lagoons; D = dehydration in units; LS = drying beds. (*) According to the Technical Standard OS 090, the density of the sludge is considered to be 1.03 Tn/m^3.

Table 9. Energy demand, area, operators and area/staff ratio

WWTP	Energy Demand (Kwh)	Area (Ha)	Operational Personnel (Operator)	Relation Area/Personnel (Ha/Operator)
Ancon	320,00	4,74	2	2,37
Cieneguilla	193 382,80	2,46	3	0,82
Julio C. Tello	4 732,48	2,37	3	0,79
San Juan	8 670,96	58,33	12	4,86
José Gálvez	1 020 700,00	7,30	8	0,91
Huáscar	13 950,72	18,00	13	1,38
Ventanilla	8 602,90	13,77	7	1,97
TOTAL	1 250 359,86	106,97	48	0.82 to 4.86

Source: Own elaboration

Table 10. Summary of sludge quality assessment of the 7 WWTPs

WWTP	Metallic Content			Biological Content		
	N. Mexico	EPA	DS. 015-2014-V	N. Mexico	EPA	DS. 015-2014-V
Ancon	Excellent	✓	✓	C	B	B
Cieneguilla	Excellent	✓	✓	C	B	B
Huáscar	Excellent	✓	✓	Excess CTt	Excess CTt	Excess CTt
J. Gálvez	Excellent	✓	✓	C	B	B
J. C. Tello	Excess Cd	✓	✓	Excess CTt	Excess CTt	Excess CTt
San Juan	Well	Exceeds Zn	Exceeds Zn	Excess CTt	Excess CTt	Excess CTt
Ventanilla	Excellent	✓	✓	C	B	B

Source: Own elaboration

C= Forest uses, soil improvement, agricultural uses; ***CTt =*** *Thermotolerant coliforms;* ***B (EPA)=*** Soil recovery, forest plantations, non-direct consumption, landfill coverage; ***B (Peru)=*** With sanitary restrictions; ***A (EPA)=*** Unrestricted (direct consumption); Does not exceed LMP = √.

Table 11. Characterization of sludge considering potential for use in soil fertility

WWTP	PARAMETERS						
	Total Nitrogen (%)	Phosphorus (%)	Potassium (%)	pH		Organic Matter (%)	Total Solids (%)
				10%	20%		
San Juan	1.20	0.0005	0.11	6.78	6.94	37.94	----
Julio C. Tello	4.67	2.1100	0.1281	6.60	6.90	37.33	----
Cieneguilla	5.52	0.2500	0.1518	7.60	8.40	44.24	----
Ancon	1.965	0.0583	1.29	6.30	7.30	31.16	----
Ventanilla	37.05	0.0900	0.052	5.29	5.45	42.70	93.10
Huáscar	2.81	0.2271	1.379	7.10	7.40	57.65	----
José Gálvez	1.03	2.421	1.47	7.50	8.00	61.62	----

Source: Own elaboration

Table 12. Quality of the compost obtained at the Pampamarca Chico - Carhuaz Plant

Plant	PARAMETERS						
	Total Nitrogen (%)	Phosphorus (%)	Potassium (%)	pH		Organic Matter (%)	Total Solids (%)
				10%	20%		
Composting and vermicomposting	> 0.6	> 0.5	> 0.3	5.00	8.00	> 30.0	----

Source: CONAM, 2006: Technical Guide for the formulation and implementation of plans for the minimization and reuse of solid waste at the municipal level.

Table 13. Characterization of sludge considering energy value

Parameters WWTP	Humidity (%)	Volatile Matter (%)	Ashes (%)	Carbon Fixed (%)	Calorific Value (*) (kcal/kg)
San Juan	12,33	38,11	46,00	15,89	4902,254
Ventanilla	10,55	37,51	45,64	12,85	5159,100

Source: Authors.

(*) Applying Gouthal formula

3.4. Commercial Value of Sludge

Fertilizer:

In order to measure the demand for this use, a random sample survey of 10 questions was applied to 100 families dedicated to agriculture. The areas of application were selected according to the potential location of customers of the future consumer market of this product, these being the surroundings of the San Juan and José Gálvez WWTPs in the districts of San Juan de Miraflores and Villa María del Triunfo respectively, due to the fact that the population settled in these areas is dedicated to the planting of various plant species. The concrete result is that there is a potential market for the use of treated sludge to fertilize farmland and it is already being used, although informally, what is missing is more dissemination regarding the quality of the dry sludge currently and the benefits of the sludge already treated to use it for this purpose, since the population is reluctant due to the perception they have about the dangerous contents that it could contain.

Energetic

In the same way, a survey was carried out, but this time applied to people knowledgeable about the cement industry (7 companies) and Peruvian brick companies (2 companies), in order to measure how much capacity the sludge product could have in this type of industry given its magnitude.

4. Discussion

4.1. Sludge Generation

In total, adding the generation of mud in the 7 WWTPs, the amount is 926315.19 Tn/Year (2537.85 Tn/day) which is equivalent to 899335.13m^3/year. The WWTP that generated the largest amount of sludge was in San Juan (7,944% with respect to the treated flow) which has Aerated Lagoons type technology, so it should be noted that in this plant the treated flow has had to be reduced precisely because of the excess generation of sludge. The WWTP with the lowest sludge generation has been that of Cieneguilla (0.004%), the only one whose type of wastewater treatment is Activated Sludge. In both cases, the sludge is dewatered in drying beds.

4.2. Contract Staff

The area per operator in the WWTPs varies approximately from 1 to 5 hectares; what is recommended by Oakley & Salguero is 4 to 8 hectares per operator, consequently, apart from the San Juan WWTP, the other WWTPs have a shortage of personnel. It should be noted that in none of the WWTPs there are specific personnel for sludge management; depending on the sludge treatment technology, the personnel are estimated to vary between 1 and 3 people (Yáñez Cossio-1993, Von Sperling-2007 and Oakley & Salguero-2010). Most of the operators of the WWTPs have a basic (secondary) level of education but have not had technical training, and the operators received technical training in EPS where they work or through external courses, It is worth mentioning that in 2014 Ministerial Resolution No. 273-2013-VIVIENDA was published that requires the presentation of a descriptive report of the WWTPs in operation and that implies the requirement of training of said personnel. In 6 of the 7 WWTPs studied, aerobic bacteria have been used for the treatment process of treated wastewater, this had an impact on the high amount of sludge that was generated; in the 7 WWTPs only the sludge has been partially dewatered (mechanical drying) which resulted in high moisture content being obtained that has led to the requirement of having to reduce this content.

4.3. Environmental Quality of Sludge

From the comparison of the concentrations obtained in the samples taken in 2015 and 2019, the following is indicated:

<u>Ancon WWTP:</u>

In the comparison of results with respect to the physical-chemical parameters, both in 2015 and 2019 the concentration of metals in any of the compared standards does not exceed. For the biological parameters, it is appreciated that the thermotolerant coliforms do not comply with any of the 3 standards, in addition to this, the other biological parameters do not comply with class A of the Peruvian Standard for sludge.

<u>Cieneguilla WWTP:</u>

In the comparison of results with respect to the physical-chemical parameters, both in 2015 and 2019 the concentration of metals in any of the compared standards does not exceed, in addition to this, the concentrations of metals remain with similar values. On the other hand, for the biological parameters, it is appreciated that the thermotolerant coliforms do not comply with any of the 3 standards, in addition to this the biological parameters do not comply with class A of the Peruvian Standard for sludge.

<u>Huáscar WWTP:</u>

In the comparison of the results of the years 2015 and 2019, with respect to the physical-chemical parameters, the concentration of metals in any of the compared standards is not exceeded. On the other hand, for the biological parameters, it is seen that thermotolerant coliforms do not comply with any of the 3 standards.

<u>José Gálvez WWTP:</u>

In the comparison of results with respect to the physical-chemical parameters, for the two years 2015 and 2019, it is observed that none exceeds the three standards; so according to Mexican standards its quality is excellent. On the other hand, for the biological parameters, it is seen that thermotolerant coliforms are within class C according to the Mexican standard; according to EPA they are in class B; and they do not comply with the Peruvian standard.

<u>Julio C. Tello WWTP:</u>

With respect to the monitoring carried out on the physicochemical parameters in 2015 and 2019 at the Julio C Tello WWTP, only in 2015, the Cadmium parameter exceeds the limits of the Mexican standard, EPA standard and Peruvian standard. Regarding the results of the monitoring of microbiological parameters, it is observed that Thermotolerant Coliforms exceed the limits of Mexican standards and in the case of the EPA standard they exceed classes A and B; the Salmonella parameter for the year 2015 exceeds the Peruvian standard for class A.

<u>San Juan WWTP:</u>

With respect to the monitoring carried out on the physicochemical parameters in 2015 and 2019 at the San Juan WWTP, it is the concentrations of Zinc that exceed the limits of the three standards, in the Mexican standard in terms of the rating of Excellent. In the results of the monitoring of microbiological parameters, it is observed that Thermotolerant Coliforms exceed the limits of the Mexican standard and in the case of the EPA standard they exceed classes A and B; the parameter Helminth and Salmonella eggs in the years 2015 and 2019 exceed the limits of the Peruvian standard.

<u>WWTP Ventanilla:</u>

According to the results of the analyses carried out on the sludge, for the years 2015 and 2019, the concentrations of the metallic parameters are below the 3 standards considered. On the other hand, regarding the microbiological parameters, both for 2015 and 2019, the parameter of Thermotolerant Coliforms exceeds the EPA, Mexican and Peruvian standards. Table 10 summarizes these results.

In summary, with respect to metal contents: given the contradictory concentrations of Cadmium existing in the sludge of the Julio C. Tello WWTP (136 mg/kg-2015 and 1.25 mg/kg-2019), considering the highest concentration normatively, it could not be used for any purpose, although the recommendation is that new samples be analyzed. In the San Juan WWTP, it is the concentration of zinc in the sludge (3257 mg/kg-2015 and 3750 mg/kg-2019) that disqualifies them for any use according to the EPA standard and the Peruvian standard, but according to the Mexican standard it can be used for urban uses without direct public contact during its application. In conclusion: a new evaluation of the raw sludge generated in the Julio C. Tello WWTP is recommended and the other 6 sludge can be used for some purpose without generating environmental deterioration.

Regarding bacterial contents: according to the Mexican standard, the sludge from the Julio C. Tello, San Juan and Ventanilla WWTPs is excellent, while the sludge generated in the other 4 plants can be used for forestry, agriculture and as a soil improver; according to the EPA standard, the sludge generated in the Ancon WWTP is the one that can be used without restriction. While those of the other 6 WWTPs can be used for soil recovery, forest plantations, non-direct consumption and solid waste coverage; according to the Peruvian standard, helminth eggs exceed LMP eggs, so you will see prior measures taken before using them.

It should be noted that there are currently methods that allow the reduction of excess concentrations of thermotolerant Cadmium, Zinc and Coliforms of raw sludge easily and at a low price. Here's how it can be done:

- Cadmium removal: by applying vermicomposteo, using worms of the species *Eisenia fetida*, the concentration can be reduced with an efficiency of up to 95%.
- Zinc removal: the interaction between an amount of the alkalizing NaOH and the amount of the coagulant $FeCl_3$ has a significant impact on the zinc removal process, reaching an efficiency of 99.90%.
- Removal of thermo-tolerant coliforms: the application of a strong oxidant, such as ozone, allows concentrations to be reduced by up to 99.9%. It also has the advantage of relatively easily inactivating very resistant germs such as viruses, Legionella, Pseudomona aeruginosa, Entamoeba histolytica, Giardia cysts, Crystosporidium parvum and Mycobacterium.

4.4. Commercial Quality of Sludge

In Table 11 and Table 12 it is observed that the content of Total Nitrogen and Organic Matter and pH of the raw sludge is very good and gives rise to think of its use as a soil fertility aid. The treatment and/or enrichment of the sludge will obviously enhance its quality.

Table 13 shows that the calorific value of the sludge from the 2 WWTPs characterized is high enough to make its energy valuation by incineration viable. However, due to the high humidity it contains when it comes out of mechanical drying, its transport would make the process very expensive. Therefore, thermal drying is recommended prior to transport it to the incineration plant, since thermal drying allows most of the intracellular water to be removed from the sludge by applying external heat. The drying product maintains its content in solid material and its humidity is reduced to 10-15%. Therefore, it is advisable to carry out this process at the same plant or nearby.

4.5. Commercial Value of Sludge

Fertilizer

Undoubtedly, the sludge from the WWTPs has economic value as a fertilizer, the value of the nitrogen content in the sludge of the stabilization lagoons is estimated at approximately S/. 0.1 per kilo of dry sludge without considering the transfer of the sludge to green areas. This is an attractive cost considering that in the market the value of a mineral fertilizer, such as ammonium nitrate, is approximately S/. 4.6 per kilo of nitrogen. As for the value of the sludge for its phosphorus content, it is estimated at approximately S/. 0.01 per kilo of dry sludge, without considering the transfer of the sludge to green areas. It should be considered that the price of mineral fertilizer, such as phosphate rock, is approximately S/. 7 to 8 per kilo of phosphorus. According to the results, the conclusion is that there is a potential market for the use of treated sludge to fertilize farmland, what is missing is a little more dissemination regarding the benefits of the use of treated sludge for this purpose, since the population is reluctant due to the perception they have about the dangerous contents it could contain.

Energetic

The general assessment regarding energy use is that there is an incipient interest in the use of sludge waste as a non-renewable energy source and that there is a lack of further promotion to enable greater acceptance.

5. Conclusions

- The sample considered in the research work, raw sludge generated in 7 WWTPs, represents 2 538 Tn/day of sludge that SEDAPAL manages only by contracting a Solid Waste Operating Company that is responsible for storing it in containers, transporting it and disposing of it in existing Sanitary Landfills in the city of Lima.
- From the environmental characterization of the raw sludge, that is, the comparison between its contents and the quality standards of the Mexican, EPA and Peruvian sludge, it is obtained that it is mostly of good quality and the effort to improve them would only imply reducing the concentrations of thermotolerant Cadmium, Arsenic and Coliforms or reducing the amount of sludge to be used, discarding those that

have excess concentrations. It should be noted that there are currently technologies that would make it possible to reduce the concentration of these three elements at low cost and high efficiency. Bacterially, there is no limitation on the use of the sludge generated in these 7 WWTPs.

- From the evaluations carried out in order to establish the nutritional content of the raw sludge, it is shown that it has better quality, in terms of total nitrogen, organic matter and pH, than the compost that is made in the Pampamarca Chico-Carhuaz-Huaraz Plant (Peru). It would only be necessary to enrich the sludge in terms of phosphorus and potassium contents.
- Two surveys were carried out in order to establish the reception capacity that this waste could have, already converted into an input. Regarding its use as fertilizer, there is a population that would be interested in its demand as long as the quality is improved through treatment and/or enrichment; moreover, there is already an informal use of it. In relation to energy purposes, demand is incipient and is basically subject to a greater diffusion of use for this purpose.
- The innovation of this research work is based on the systemic approach of this environmental business, commercialization of treated sludge, within the framework of integration of economy, labor and law. It represents a new way of doing green business, understood as those that reduce the environmental impact of economic sectors with the aim of achieving sustainable levels. It is obvious that innovation is required with respect to how they are currently managed, since the treatment, enrichment and commercialization of raw sludge require incorporating it into the value chain.

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REFERENCES

[1] D. Valchev *et al.*, "Valuable elements in sludge from eight municipal wastewater treatment plants in relation to their recovery potential", *Environ. Sci. Eur.*, vol. 36, no. 1, 2024.

[2] A. Bringas, E. Bringas, R. Ibañez, y M.-F. San Román, "Tracing Gadolinium levels throughout wastewater treatment: Insights from a yearly assessment in northern Spain", *Sci. Total Environ.*, vol. 948, p. 174819, 2024.

[3] C. C. Castro-Jiménez, J. C. Saldarriaga-Molina, y E. F. García, "Physical-chemical characterisation of an alum-based water treatment sludge in different raw water turbidity scenarios", *Heliyon*, vol. 10, no. 17, p. e37579, 2024.

[4] L. di Bitonto, V. Locaputo, y C. Pastore, "Solventless recovery of lipids from urban sewage sludge: How to sustainably turn a waste into a valuable source of oleochemicals", *Chem. Eng. J.*, vol. 494, p. 152991, 2024.

[5] F. J. Sousa, C. F. Jesus, J. R. Góis, N. A. M. Pereira, y F. E. Antunes, "Microcrystalline cellulose and by-products from the pulp and paper industry as reinforcing fibres for polybutylene succinate-based composites: A comparative study", *J. Reinf. Plast. Compos.*, vol. 43, no. 15–16, pp. 912–925, 2024.

[6] I. W. K. Suryawan *et al.*, "Enhancing energy recovery from Wastewater Treatment Plant sludge through carbonization", *Energy Nexus*, vol. 14, p. 100290, 2024.

[7] T. Yilmaz *et al.*, "Performance of a high-rate membrane bioreactor for energy-efficient treatment of textile wastewater", *J. Environ. Manage.*, vol. 358, p. 120845, 2024.

[8] R. Zarina y L. Mezule, "Opportunities for resource recovery from Latvian municipal sewage sludge", *Heliyon*, vol. 9, no. 10, p. e20435, 2023.

[9] D. Skrzypczak *et al.*, "Maximizing the potential of leachate from sewage sludge as a sustainable nutrients source to alleviate the fertilizer crisis", *J. Environ. Manage.*, vol. 338, p. 117794, 2023.

[10] L. Aarikka-Stenroos, M. Kokko, y E.-L. Pohls, "Catalyzing the circular economy of critical resources in a national system: Case study on drivers, barriers, and actors in nutrient recycling", *J. Clean. Prod.*, vol. 397, p. 136380, 2023.

[11] F. C. Muniz Sacco, Z. Frkova, S. Venditti, C. Pastore, C. Guignard, y J. Hansen, "Operation of a pilot-scale lipid accumulation technology employing parameters to select Microthrix parvicella for biodiesel production from wastewater", *Bioresour. Technol.*, vol. 369, p. 128498, 2023.

[12] S. Arnone *et al.*, "Black soldier fly (Hermetia illucens L.) as a high-potential agent for bioconversion of municipal primary sewage sludge", *Environ. Sci. Pollut. Res. Int.*, vol. 29, no. 43, pp. 64886–64901, 2022.

[13] O. Gencel, O. Kizinievic, E. Erdogmus, V. Kizinievic, M. Sutcu, y P. Muñoz, "Manufacturing of fired bricks derived from wastes: utilization of water treatment sludge and concrete demolition waste", *Arch. Civ. Mech. Eng.*, vol. 22, no. 2, 2022.

[14] M. M. Fouad, A. S. El-Gendy, M. M. H. Khalil, y T. M. A. Razek, "Aluminum sulfate regeneration from surface water treatment waste in Cairo, Egypt", *Environ. Sci. Pollut. Res. Int.*, vol. 28, no. 43, pp. 61450–61459, 2021.

[15] W. Bolesta, M. Głodniok, M. Pieczonka, y K. Styszko, "Antibiotics and endocrine disruptors in sewage sludge samples in terms of its agriculture use", *Desalination Water Treat.*, vol. 232, pp. 280–297, 2021.

[16] A. Hurynovich, M. Kwietniewski, y V. Romanovski,

"Evaluation of the possibility of utilization of sewage sludge from a wastewater treatment plant – case study", *Desalination Water Treat.*, vol. 227, pp. 16–25, 2021.

[17] R. Avila, E. Carrero, T. Vicent, y P. Blánquez, "Integration of enzymatic pretreatment and sludge co-digestion in biogas production from microalgae", *Waste Manag.*, vol. 124, pp. 254–263, 2021.

[18] A. A. S. Ghaleb *et al.*, "Sugarcane bagasse as a co-substrate with oil-refinery biological sludge for biogas production using batch mesophilic anaerobic co-digestion technology: Effect of carbon/nitrogen ratio", *Water (Basel)*, vol. 13, no. 5, p. 590, 2021.

[19] S. Salehin *et al.*, "Effects of aging of ferric-based drinking water sludge on its reactivity for sulfide and phosphate removal", *Water Res.*, vol. 184, p. 116179, 2020.

[20] M. Stylianou *et al.*, "Physicochemical and structural characterization of biochar derived from the pyrolysis of biosolids, cattle manure and spent coffee grounds", *J. Energy Inst.*, vol. 93, no. 5, pp. 2063–2073, 2020.

[21] M. Smol, "Inventory of wastes generated in Polish sewage sludge incineration plants and their possible circular management directions", *Resources*, vol. 9, no. 8, p. 91, 2020.

[22] S. Guerra-Rodríguez, P. Oulego, E. Rodríguez, D. N. Singh, y J. Rodríguez-Chueca, "Towards the implementation of circular economy in the wastewater sector: Challenges and opportunities", *Water (Basel)*, vol. 12, no. 5, p. 1431, 2020.

[23] S. Di Fraia, N. Massarotti, M. V. Prati, y L. Vanoli, "A new example of circular economy: Waste vegetable oil for cogeneration in wastewater treatment plants", *Energy Convers. Manag.*, vol. 211, p. 112763, 2020.

[24] A. López, J. Rodríguez-Chueca, R. Mosteo, J. Gómez, y M. P. Ormad, "Microbiological quality of sewage sludge after digestion treatment: A pilot scale case of study", *J. Clean. Prod.*, vol. 254, p. 120101, 2020.

[25] I. Pecorini *et al.*, "Evaluation of MSW compost and digestate mixtures for a circular economy application", *Sustainability*, vol. 12, no. 7, p. 3042, 2020.

[26] R. D. Farias, C. M. García, T. C. Palomino, F. Andreola, I. Lancellotti, y L. Barbieri, "Valorization of Agro-industrial wastes in lightweight aggregates for agronomic use: Preliminary study", *Tuiasi.ro*. [En línea]. Disponible en: http://www.eemj.icpm.tuiasi.ro/pdfs/vol16/no8/5_47_Farias_17.pdf. [Consultado: 16-sep-2024].

[27] P. Guedes, N. Couto, E. P. Mateus, y A. B. Ribeiro, "Phosphorus recovery in sewage sludge by electrokinetic based technologies: A multivariate and circular economy view", *Waste Biomass Valorization*, vol. 8, no. 5, pp. 1587–1596, 2017.

[28] S. Song *et al.*, "Plant transpiration inspired biomass-derived solar evaporator for highly efficient solar vapor generation", *Sep. Purif. Technol.*, vol. 354, p. 129413, 2025.

[29] Y. Ouyang *et al.*, "ZnCl2 and thiourea co-modified biochar for effectively removing quinclorac in water and soil: Mechanism and alleviating its phytotoxicity on tobacco plants", *Sep. Purif. Technol.*, vol. 350, p. 127865, 2024.

[30] Q. Ma, W. Huang, W. Xu, H. Zhou, D. Hashan, y D. She, "Synergistic mechanisms of lignin-based novel materials and leaf-surface selenium fertilizer in alleviating drought and heavy metal stress", *Ind. Crops Prod.*, vol. 222, no. 119487, p. 119487, 2024.

[31] F. Yang, S. Wu, y Z. Yu, "Comparative analysis of whole chloroplast genomes of three common species of Nekemias from vine tea", *Sci. Rep.*, vol. 14, no. 1, pp. 1–14, 2024