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Characterization of sewage sludge generated in Rio de Janeiro, Brazil, and perspectives for agricultural recycling

Caracterização do lodo de esgoto gerado no Rio de Janeiro, Brasil, e perspectivas para reciclagem agrícola

Alan Henrique Marques de Abreu^{1*}; Paulo Sérgio dos Santos Leles²; Jorge Makhlouta Alonso¹; Elton Luis da Silva Abel¹; Ricardo Rodrigues de Oliveira³

Abstract

Sanitary sewage collection and treatment is a serious environmental problem in Brazilian cities, as well as the destination of solid waste resulting from this process, i.e. the sewage sludge, a substance rich in organic matter and nutrients, which is normally discarded in landfills. The aim of this study was to characterize the sewage sludge generated in four treatment stations in Rio de Janeiro State, Brazil and check if they meet the legal criteria of the National Environment Council (CONAMA), Resolution No. 375/2006. It also focused on analyzing the perspectives for its agricultural recycling based on the potential demand for main agricultural crops grown in Rio de Janeiro State. Samples from eight sewage sludge lots from four treatment stations located in the metropolitan area of Rio de Janeiro were analyzed. These stations receive and treat only domestic sewage by activated sludge system. For chemical and biological characterization of these lots, representative samples were collected and analyzed according to parameters of CONAMA Resolution No. 375/2006. In order to analyze the perspectives of agricultural recycling of sewage sludge in Rio de Janeiro State, 10 crops with the largest cultivated area in the state were surveyed and analyzed which of them are apt to receive sewage sludge as fertilizer and/or soil amendment. To determine the potential demand for sewage sludge in agriculture, the area occupied by these crops were multiplied by each fertilizer recommendation considering the sewage sludge as fertilizer. The analyzed sludge presented a high content of nutrients and organic matter and was included in the parameters of heavy metals, pathogenic agents, and bacteriological indicators stipulated by CONAMA Resolution No. 375/2006. The agricultural panorama of Rio de Janeiro State is favorable for agricultural recycling of sewage sludge since there is a great potential demand for this residue and, among the 10 agricultural crops with the largest cultivated area in the state, sludge can be used as fertilizer or soil amendment in eight of them. The implementation of a State Sewage Sludge Recycling Program could dispose of this material in a more sustainable way, as well as improve the quality of agricultural soils and reduce costs with chemical fertilizers, bringing positive results for sanitation companies and producers.

Key words: Biosolid. Solid waste. Organic fertilization.

Resumo

A coleta e tratamento do esgoto sanitário é um grave problema ambiental nas cidades brasileiras, bem

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como a destinação do resíduo sólido resultante desse processo, o lodo de esgoto, substância rica em matéria orgânica e nutrientes, que normalmente é descartada em aterros sanitários. Objetivou-se com este trabalho caracterizar o lodo de esgoto gerado em quatro estações de tratamento do estado do Rio de Janeiro e verificar se os mesmos atendem aos critérios legais presentes na resolução CONAMA nº 375/2006. Com o trabalho visa-se ainda analisar as perspectivas para a reciclagem agrícola deste material, com base na demanda potencial das principais culturas agrícolas cultivadas no estado do Rio de Janeiro. Foram analisadas amostras de oito lotes de lodo de esgoto, oriundos de quatro estações de tratamento, localizadas na região metropolitana do Rio de Janeiro, que recebem e tratam apenas esgotos domésticos, pelo sistema de lodos ativados. Para caracterização química e biológica desses lotes coletaram-se amostras representativas que foram analisadas segundo os parâmetros contidos na Resolução nº 375/2006 do CONAMA. Para analisar as perspectivas de reciclagem agrícola do lodo de esgoto no estado do Rio de Janeiro, foram levantadas as 10 culturas com maior área plantada no estado e analisadas quais destas são aptas a receberem o lodo de esgoto como fertilizante e/ou condicionador de solos. Para determinação da demanda potencial de uso do lodo de esgoto na agricultura foi levado em consideração a área ocupada no estado pelas culturas aptas a receber o lodo e multiplicado pela recomendação de adubação da cultura, considerando o lodo de esgoto como fertilizante. Os lodos analisados apresentaram elevado teor de nutrientes e matéria orgânica e enquadraram-se nos parâmetros de metais pesados, agentes patogênicos e indicadores bacteriológicos estipulados pela resolução CONAMA nº 375/2006. O panorama agrícola do estado do Rio de Janeiro se mostra favorável para a reciclagem agrícola do lodo de esgoto, visto que existe uma grande demanda potencial e dentre as dez culturas agrícolas com maior área plantada no estado, em oito pode-se utilizar o lodo como fertilizante ou condicionador de solos. A implementação de um Plano Estadual de reciclagem do lodo de esgoto poderia dispor este material de forma mais sustentável, além de melhorar a qualidade dos solos agrícolas e diminuir os custos com fertilizantes químicos, o que traz reflexos positivos tanto para as empresas geradoras de lodo, como para os produtores rurais.

Palavras-chave: Biossólido. Resíduos sólidos. Adubação orgânica.

Introduction

A sewage treatment station (STS) provides an important environmental service to society by collecting and treating millions of liters of sewage daily, thus avoiding that considerable organic load reaches water bodies. After treatment, water is returned to springs, remaining in the stations the solid waste called sewage sludge (ABREU, 2014).

In Brazil, only 49.8% of sewage is collected, being treated 70.9% of this sewage (BRASIL, 2016). In regions with better sanitation conditions, the final disposal of residues from sewage treatment is a matter of concern. In Rio de Janeiro State alone, about 365 tons of sewage sludge is produced per day, totaling 133,225 tons per year, being disposed of in landfills almost all of it (PERS, 2014). However, this scenario tends to change firstly due to society's increased environmental awareness, which demands that the National Solid Waste Policy (BRASIL, 2010) be duly complied with allocating

residues in a more sustainable way. Secondly, due to the difficulty of opening new landfills and outsourcing or closing public landfills, which has raised the cost of disposal of these residues to STSs (BIELSCHOWSKY, 2014).

This material has in its composition high contents of nutrients and organic matter that could be reused, increasing crop productivity and decreasing the dependence on chemical fertilizers (CHIBA et al., 2008; LOBO et al., 2015; LOZADA et al., 2015). In some countries, such as the United States, Australia, France, the United Kingdom, and Spain, agricultural recycling of sludge is widespread, with some regions disposing up to 80% of the sludge generated at their stations for soil applications (BOURIOUG et al., 2015; LU et al., 2012; MININNI et al., 2015; PRITCHARD et al., 2010). In Brazil, the main form of final disposal of sewage sludge has still been by means of landfills, despite its great potential for agricultural use.

Agricultural recycling can be an environmentally correct alternative to disposing of this residue, with advantages for STSs, which dispose of their residues in a more sustainable way, and producers, who receive a material rich in nutrients and organic matter. However, before implementing a sewage sludge recycling program, the composition of the generated material in STSs needs to be known and verified whether it comply with the current legislation and meet the regional demand thus justifying this alternative.

Based on the above, the aim of this study was to characterize chemically and biologically the sewage sludge generated in four treatment stations of the metropolitan region of Rio de Janeiro, Brazil. Also, it focused on verifying whether it meets CONAMA Resolution No. 375/2006 and analyzing the perspectives for its agricultural recycling, based on the potential demand to attend the fertilization requirements of agricultural crops grown in Rio de Janeiro State.

Material and Methods

Samples from eight sewage sludge lots from four STSs that receive and treat only domestic sewage and are located in the metropolitan area of Rio de Janeiro were analyzed. These STSs are operated and maintained by the State Water and Sewage Company of Rio de Janeiro (CEDAE). They have the following treatment processes: STS Alegria ($5,000 \text{ L s}^{-1}$) and STS Ilha do Governador (535 L s^{-1}), a secondary treatment with activated sludge system, biological anaerobic stabilization, centrifugal dewatering, and drying in semipermeable beds; STS Sarapu  ($1,500 \text{ L s}^{-1}$), a secondary treatment with activated sludge system, centrifugal dewatering, and thermal drying; and STS Barra da Tijuca ($1,600 \text{ L s}^{-1}$), a primary treatment with centrifugal dewatering and thermal drying.

CEDAE has an internal sewage sludge recycling project to produce Atlantic Forest seedlings in its forest nurseries. Therefore, the analyzed

lots coincided with the need for analysis by this project. The lots analyzed were: I-STs Alegria, December 2012; II-STs Alegria, November 2014; III-STs Barra da Tijuca, August 2013; IV-STs Ilha do Governador, November 2014; V-STs Ilha do Governador, February 2015; VI-STs Ilha do Governador, January 2016; VII-STs Sarapu , August 2013; and VIII-STs Sarapu , November 2014.

For characterizing and assessing the agronomic potential of sludge lots from different STSs, representative samples of materials were collected and analyzed chemically and biologically according to standards contained in Annex IV of CONAMA Resolution No. 375/2006 (BRASIL, 2006). Thus, for total N determination, the Kjeldahl method was used, in which 0.05 g of oven-dried sample (65°C) was diluted in 3 mL of concentrated H_2SO_4 . Subsequently, this solution was led to a digester block at 360°C for 3 h. For distillation, 20 mL NaOH solution (10 mol L^{-1}) was added. Distilled N was added to 20 mL H_3BO_3 solution (20 g L^{-1}), which was titrated with a standard H_2SO_4 solution ($0.0025 \text{ mol L}^{-1}$).

The elements P, K, Ca, Mg, As, Ba, Cd, Cr, Cu, Hg, Ni, Pb, Se, and Zn were extracted in a microwave oven by using the SW-846 test method 3051 (USEPA, 2010). Samples of 0.5 g of sewage sludge were oven dried at 65°C and mixed in 10 mL of concentrated nitric acid. After 15 minutes, samples were placed in a microwave oven for 30 minutes. K determination was performed by flame photometry and the other elements by atomic emission spectrometry by inductively coupled plasma (ICP-AES).

Organic matter was defined by organic carbon content, which was determined by the Walkley and Black method, being subsequently multiplied by the van Bemmelen factor, equivalent to 1,724 (CARMO; SILVA, 2012). The value of pH was determined using a sample of 2 g of sewage sludge diluted in 20 mL of deionized water, shaken for 5

minutes on a horizontal circular shaker at 200 rpm. After 30 minutes of rest, pH was determined by means of a bench pH meter.

Microbiological characterization of sewage sludge for the presence of thermotolerant coliforms, viable eggs of helminths, and *Salmonella* sp., which correspond to the presence of harmful pathogens to human health, was carried out by a specialized laboratory. This characterization was performed according to US EPA part 503 (2003), as stipulated by CONAMA Resolution No. 375/2006 (BRASIL, 2006). Through these analyses, sewage sludge can be classified into class A (excellent quality) or B (greater restrictions of use) depending on the presence and/or concentrations of microorganisms in its composition. Enteric virus parameter was not assessed due to the difficulty of finding a laboratory that performed this analysis. Microbiological and heavy metal parameters were compared to the maximum allowed by CONAMA Resolution No. 375/2006 (BRASIL, 2006) and assessed whether they comply with the current legislation on sludge application to soil.

In order to analyze the perspectives for agricultural recycling of sewage sludge in Rio de Janeiro State, data based on the year 2014 from the Systematic Survey of Agricultural Production, prepared and made available by the Technical Assistance and Rural Extension Company (EMATER) of Rio de Janeiro, were used. The 10 agricultural crops with the largest cultivated area in Rio de Janeiro State were surveyed and analyzed regarding their aptitude to receive sewage sludge as fertilizer and/or soil amendment, according to the Article 12 of CONAMA Resolution No. 375/2006. To determine the potential demand for sewage sludge, the area occupied by these crops were multiplied by the fertilizer recommendation considering the sewage sludge as fertilizer for each crop, obtained in the literature. When more than one recommendation was found, the average of them was taken into account for calculation.

Results and Discussion

The high content of nutrients in the sewage sludge lots (Table 1) corroborates the results by diverse authors. Those of Aguilera et al. (2007) who characterized the sludge from three STSs in Chile; MTSHALI et al. (2014) who analyzed the sludge from seven STSs in Swaziland (Southern Africa); and Carvalho et al. (2015) who analyzed five different sludge from two STSs in São Paulo State, Brazil. All of these studies and the current one reported high contents of organic matter and nutrients in sewage sludge, mainly N and P. Sampaio (2010), analyzing sludge produced in different STSs in Brazil, found contents of N ranging from 22.5 to 55.3 g kg⁻¹, P from 6 to 30 g kg⁻¹, K from 0.1 to 3.9 g kg⁻¹, and organic matter from 410 to 713 g kg⁻¹. Thus, in general, the analyzed sludge lots are within the observed patterns for sludge generated in Brazilian stations.

In addition, the difference in nutrient concentration among the sludge is related not only to the composition of sewage generated in the drainage basin but also to the treatment type used at each STS. The STS Barra da Tijuca, for instance, has treatment at a primary level, which, according to Bielschowsky (2014), tends to generate sludge with lower nutrient concentrations than that produced in STS with secondary treatment, as in the other sludges analyzed in this study. Another fact observed was the variability of N content in the sludge from STS Ilha do Governador. This variability possibly occurred as a function of drying method by means of open-air semipermeable beds, which may have favored the percolation and volatilization of N when it remained for long periods in the drying process.

Sewage sludge lots analyzed presented N contents varying from 14.24 to 42.33 g kg⁻¹ of sewage sludge on the dry basis (Table 1). Carvalho et al. (2015), analyzing five different sludge from STSs in São Paulo, Brazil, found similar N contents, which ranged from 17.40 to 42.63 g kg⁻¹ on the dry basis. In the sewage sludge, the largest

N portion is in an organic form and, therefore, it is readily available for plants only after organic matter degradation (CARVALHO et al., 2015; NASCIMENTO, 2016). This characteristic causes the N present in sewage sludge to be released slowly into the system, which may be favorable when compared to chemical fertilizers. Considering

the strong Brazilian dependence on N import and relatively high costs for its acquisition, recycling of sludge and, consequently, N contained in it can be not only an environmental strategy but also a relevant economic strategy (ANDRADE et al., 2010).

Table 1. Nutrient and organic matter contents (mg kg⁻¹) present in sludge lots of sewage treatment stations in the metropolitan area of Rio de Janeiro, RJ, Brazil.

STS	Lot	N	P	K	Ca	Mg	MO	pH
Alegria	I	38,83	6,16	5,00	2,36	0,15	544,1	5,5
Alegria	II	32,94	9,56	3,99	2,11	5,45	572,8	5,1
Barra	III	18,37	8,91	2,09	2,39	5,69	398,3	7,3
Ilha	IV	33,47	5,42	1,82	1,56	3,22	578,8	5,3
Ilha	V	28,78	5,22	1,57	1,74	3,22	589,4	5,0
Ilha	VI	14,24	5,53	4,01	18,51	5,83	598,7	6,5
Sarapuí	VII	42,33	17,23	2,73	1,35	2,95	515,9	6,3
Sarapuí	VIII	39,81	12,24	3,07	8,59	2,69	513,2	6,5
Mean	-	31,09	8,78	3,03	4,83	3,65	538,9	5,8
SD	-	10,17	4,24	1,21	6,01	1,93	65,3	0,9

N-Kjedhal method; P, Ca, and Mg-ICP-OES; K-flame photometry; OM-Walkley and Black method; pH-H₂O. SD: standard deviation.

When analyzing the need to complement sewage sludge with nitrogen fertilizers for sugarcane fertilization, Chiba et al. (2008) found results that prove the efficiency of sludge in fertilizing this crop. The authors observed that a sludge dose corresponding to 120 kg ha⁻¹ of total N (10.8 tons) was enough to supply the requirements for sugarcane cultivation, without complementation with other nitrogen sources. Taking into account that sugarcane is the most cultivated agricultural crop in Rio de Janeiro, corresponding to approximately 49% of the total agricultural area cultivated in the state (EMATER, 2014); sludge reuse for fertilizing this crop can be one of the strategic alternatives for the state's agricultural sector.

P contents in the sludge lots analyzed ranged from 5.22 to 17.23 g kg⁻¹, values close to those

observed in other studies (CARVALHO et al., 2015; CONSUEGRA et al., 2015; MACHADO; TRANNIN, 2015; SAMPAIO, 2010). Sludge lots from STS Ilha do Governador presented the lowest P contents whereas STS Sarapuí presented the highest contents of this nutrient. Sewage sludge recycling for P reuse has a high economic and environmental potential since this is an essential element for all living organisms, being fundamental for food production. Thus, with the current rate of exploitation and use of P, the estimation is that its reserves in the world will last for only 50 to 100 years (MARTÍNEZ et al., 2014).

In tropical and subtropical soils, as in Brazil, the dependence of phosphate fertilization is even more pronounced since P is strongly adsorbed in clay minerals, presenting a very low availability to plants,

which requires the application of large amounts of phosphate fertilizers, most of which imported at a high cost (ANDRADE et al., 2010; MACHADO et al., 2011). Due to the decrease in quantity and quality of phosphate rocks, the tendency is that phosphorus gets increasingly expensive, which leads to an urgent need to seek new sources and develop sustainable methods for recycling this element, mainly through sewage sludge (EGLE et al., 2015; MARTÍNEZ et al., 2014).

K is a highly soluble substance, being found in lower concentrations in dry sewage sludge since this nutrient is diluted and solubilized in wastewater (BERTON; NOGUEIRA, 2010). The analyzed sludge presented K contents varying from 1.82 to 5.00 g kg⁻¹, values close to those observed by Nascimento (2016), who analyzed sludge from 19 STSs in São Paulo State and found K contents varying from 0.50 to 4.60 g kg⁻¹. Fuentes et al. (2010), Mtshali et al. (2014), and Suhadolc et al. (2010) also observed a low K content found in sewage sludge. Thus, for agricultural recycling, depending on crop requirements, sludge should be enriched with K sources.

Ca was found in contents ranging from 1.35 to 18.51 g kg⁻¹ of sludge on a dry basis. In the studied STSs, liming treatment is not adopted for sludge cleaning, justifying these lower Ca contents in the sludge when compared to other studies (CARVALHO et al., 2015; CONSUEGRA et al., 2015; NASCIMENTO, 2016). Sludge from lot VI (STS Ilha do Governador), analyzed in January 2016, presented higher Ca content than the other samples, which may be the result of some punctual source of this nutrient in the drainage basin. According to Carneiro et al. (2005), the presence of calcium oxide can raise sewage sludge pH and favor losses through volatilization and leaching, which may explain the lower N contents in lot VI when compared to the other two lots from STS Ilha do Governador.

Mg contents found in the analyzed lots ranged from 0.15 to 5.83 g kg⁻¹. Nascimento (2016), when analyzing the chemical composition of sludge from 19 STSs in São Paulo State, found Mg contents ranging from 1.0 to 4.5 g kg⁻¹. This is an element present in the sludge essentially in a mineral form, i.e. inorganic, and even small sewage sludge doses can meet the needs for this nutrient depending on the crop demand (TSUTIYA, 2001).

The analyzed sludge presented organic matter content varying from 51.6 to 57.9%. A high content of organic matter in the sludge generated in STSs is one of the main attributes to be taken into account for agricultural recycling of this material. Carvalho et al. (2015), when analyzing the organic fraction of five different sludge, found that more than 70% of carbon and 80% of nitrogen are in the organic compartment of sewage sludge. For this reason, sludge has been widely used as an amendment to improve soil chemical and physical characteristics and its application to soil has been indicated as one of the actions to mitigate climate change aiming at increasing the organic matter stock and hence soil carbon (BONINI et al., 2015; OUIOMET et al., 2015).

Sewage sludge application is a beneficial alternative to recycle organic matter and nutrients as it improves soil physical, chemical, and biological properties, as well as improve vegetation establishment in degraded environments and assist the nutrition of agricultural crops (BORGES et al., 2009; LOBO et al., 2015; LU et al., 2012; SAMPAIO et al., 2016). However, before being used in agricultural crops and in addition to meeting the nutritional needs of plants and improving soil characteristics, sewage sludge needs to comply with the principles of environmental safety, with safe levels of heavy metals and offering no chemical or microbiological risk to human health or environment.

For all sewage sludge lots analyzed, concentrations of heavy metals were lower than the

maximum allowed by legislation, characterizing them as viable for agricultural use regarding the risk of contamination by heavy metals (Table 2). Tiruneh et al. (2014) analyzed the chemical composition of sewage sludge from seven treatment stations in

Switzerland and found higher concentrations of heavy metals in sludge from STSs that received industrial sewage. The sludge analyzed in this study was from stations that receive only domestic loads, which justifies the low levels of heavy metals found.

Table 2. Contents of potentially toxic heavy metals (mg kg⁻¹) in sludge lots of sewage treatment stations in the metropolitan area of Rio de Janeiro, RJ, Brazil.

STS	Lot	As	Ba	Cd	Cr	Cu	Hg	Ni	Pb	Se	Zn
Alegria	I	2,6	157	0,20	70,1	267	0,03	40,2	197	5,9	681
Alegria	II	0,004	406	1,83	80,2	272	0,01	26,9	152	0,004	586
Barra	III	0,004	180	1,01	66,2	193	0,09	36,4	34	0,004	1007
Ilha	IV	3,65	182	1,29	42,7	240	0,02	16,2	71	0,004	675
Ilha	V	0,004	159	1,01	40,1	204	0,01	14,9	61	0,004	619
Ilha	VI	0,004	139	0,89	39,0	277	0,01	13,2	64	0,004	1079
Sarapuí	VII	0,004	567	0,99	55,3	117	0,01	11,1	39	0,004	366
Sarapuí	VII	0,004	41,1	0,19	20,3	23	0,01	11,2	6	0,004	43
Conama*	-	41	1300	39	1000	1500	17	420	300	100	2800
Mean	-	0,8	228,9	0,9	51,7	199,1	0,02	21,3	78,0	0,74	632,0
SD	-	1,47	170,6	0,54	19,7	89,0	0,03	11,7	64,2	2,08	330,5

*Maximum values of heavy metals present in the sludge allowed by CONAMA Resolution No. 375/2006.

Lots I and II, from STS Alegria, arouse the most attention because, although Pb contents are below the limit stipulated by legislation (300 mg kg⁻¹), they represent 66 and 51% of the maximum limit, respectively. Considering that the STSs analyzed admit to receiving only domestic sewage, these Pb contents may indicate clandestine discharges in the sewage disposal system since the contents observed for these two samples are more similar to those observed in sludge from STSs that receive industrial loads than those exclusively domestic (PINHEIRO; SÍGOLO, 2007; TIRUNEH et al., 2014).

When analyzing the average concentration of heavy metals in the lots sampled regarding the maximum levels allowed by CONAMA Resolution No. 375/2006, the order of attention was Pb> Zn> Ba> Cu> Cr> Ni> Cd> As> Se> Hg, which are respectively 26, 23, 18, 13, 5, 2, 2, 1, and 0,1% of the

maximum limit for agricultural use. A concentration below the maximum limits allowed does not necessarily eliminate the risks of contamination since successive applications may lead to the accumulation of these metals in the agricultural soil (FJÄLLBORG et al., 2005).

Andrade et al. (2014) analyzed the heavy metal contents in two corn-cultivated Oxisols, which received thirteen annual applications of 5, 10, and 20 t ha⁻¹ of sewage sludge, and found an increased content of heavy metals in the soil surface layer. Despite the fact that the contents were below the values determined by CONAMA Resolution No. 420/2009 (BRASIL, 2009), the authors warned that with more sludge application of heavy metal contents, these soils would reach a level of toxicity. Therefore, recycling of sewage sludge to agricultural crops that require successive applications requires

constant monitoring to avoid negative effects.

Another important parameter is the analysis of pathogenic agents and bacteriological indicators, which are used to identify possible risks of microbiological contamination and classify sewage sludge in classes A or B. According to the data presented in Table 3, all sludge samples can be classified as belonging to class A, indicating that pathogenic microorganism concentration in these

materials is below the maximum allowed according to CONAMA Resolution No. 375/2006. Bittencourt (2014) observed the difficulty of analyzing the concentration of virus in sewage sludge in Brazil, where few laboratories perform the tests and methodologies for collection and analysis are complex and very costly, suggesting that the need for this analysis should be revised.

Table 3. Concentration of pathogenic microorganisms in sludge lots of sewage treatment stations in the metropolitan area of Rio de Janeiro, RJ, Brazil.

STS	Lot	Thermotolerant coliforms (MLN g ⁻¹ TS)	Viable eggs of helminths (eggs g ⁻¹ TS)	<i>Salmonella</i> sp. (Present or absent in 10 g TS ⁻¹)
Alegria	I	< 0,04	< 0,01	Absent
Alegria	II	< 0,04	< 0,01	Absent
Barra	III	< 0,04	< 0,01	Absent
Ilha	IV	13,62	< 0,01	Absent
Ilha	V	7,29	< 0,01	Absent
Ilha	VI	< 0,04	< 0,01	Absent
Sarapuí	VII	< 0,04	< 0,01	Absent
Sarapuí	VIII	< 0,04	< 0,01	Absent
CONAMA*	-	< 1000	< 0,25	Absent

*Maximum values allowed by CONAMA Resolution No. 375/2006; MLN: most likely number; TS: Total solids.

For the use of sewage sludge on agricultural and forest areas, it should pass through a stabilization process to reduce pathogens, vector attraction potential elimination, and generation of odors (BRASIL, 2006). In spite of having different treatments, based on the results observed, treatment processes used by STSs have been efficient for sludge stabilization since all samples were below the maximum limits allowed by legislation.

Class A microbiological standards are the same as those set by the USA legislation, being a standard worldwide accepted for promoting the necessary public health safety of the exposed population. Although Brazilian legislation accepts the same parameters adopted worldwide, it makes severe

restrictions on the application of class A sludge, even though there are no scientific and technical studies to justify it (SAMPAIO, 2010). Legislation in the United States and Australia does not impose restrictions on the use of class A sludge and it is even sold for domestic use in some USA supermarkets (SAMPAIO, 2010). In Brazil, the use of any type of sewage sludge in crops whose plant edible part is in contact with soil is expressly prohibited, as in root and tuber cultivation, in addition to some restrictions in relation to vegetables and pastures (BRASIL, 2006).

The analyzed sludges, in addition to presenting a high nutritional potential for agricultural use, were adequate to current legislation regarding the contents

of heavy metals and biological contaminants. It is important to point out that, as can be observed from the presented data, sewage sludge composition has some variability from an STS to another mainly as a function of the drainage basin, the form of treatment used, and pathogen reduction method applied.

Table 4 presents the 10 most cultivated agricultural crops in Rio de Janeiro State, which represent 83% of the total cultivated area and 64.5% of annual agricultural revenues (EMATER, 2014). Among them, only cassava and lettuce could not be fertilized with sewage sludge considering the Article 12 of CONAMA Resolution No. 375/2006 (BRASIL, 2006), which prohibits sewage application in crops whose edible part is in direct contact with soil. The other crops are strategically important for future

sewage sludge recycling actions since they present a potential demand of 2,902,943 tons of sewage sludge, which corresponds to approximately 22 times the annual production of sewage sludge from the entire state (PERS, 2014). Thus, all sewage sludge currently generated by STSs present in the state would meet only 4.59% of the potential demand for these eight agricultural crops. Literature findings have shown greater differences between the highest and the lowest sewage sludge recommended dose per hectare for sugarcane, banana, orange, and corn. Such fact can be attributed mainly to studies carried out in different conditions of climate, soil, genetic material, research methodologies, and mainly different sludges with different nutrient contents, directly influencing the recommendation to meet the nutritional crop demand.

Table 4. Potential demand for sewage sludge to be used in the 10 crops with the largest cultivated area in Rio de Janeiro State, Brazil.

Crop	Area (ha)	Recommendation* (t ha ⁻¹)	Average recom- mendation (t ha ⁻¹)	Potential de- mand (tons)	Reference
Sugarcane	85.562	10,8 - 42	22,75	1.946.535	Chiba et al. (2009); Franco et al. (2010); Silva et al. (1998)
Banana	14.604	9,0 - 52	31,40	458.565	Barbosa (2008); Coelho et al. (2011); Fortes (2011); Melo and Ligo (2006)
Coffee	12.344	9,0 - 11,5	10,25	126.526	Gonçalves (2005); Martins et al. (2005)
Cassava	8.292	-	-	0	Brasil (2006)
Orange	7.212	10,8 - 40	18,36	132.412	Canet et al. (1997); Lambert (2013); Lanza (2014); Romeiro (2012); Romeiro et al. (2014)
Lettuce	4.497	-	-	0	Brasil (2006)
Green coconut	3.613	12,87	12,87	46.499	Estimated by demand for N by culture
Corn	2.932	26 - 75	46,50	136.338	Gomes et al. (2007); Junio et al. (2011, 2013); Quintana et al. (2012)
Pineapple	2.629	8,80	8,80	23.135	Maia (2013)
Tomato	2.579	12,77	12,77	32.933	Dantas (2010)
Total	144.264	-	-	2.902.943	-

*Highest and lowest recommendation found in the literature.

Although sewage sludge has a high potential for agricultural recycling, it is necessary to identify the regions of greatest potential and deepen the logistics studies in order to verify the viability of transport to these areas. When analyzing the sewage sludge recycling program in Paraná State, Brazil, Bittencourt et al. (2014) observed that the distance between STS and application areas ranged from 32 to 213 km, demonstrating the possibility of working at a regional level since not always the largest generators of sludge are the municipalities with the largest agricultural production.

Northern and northwestern Rio de Janeiro State are regions of a great agricultural importance, responsible for 63% of the state's cultivated agricultural area, with more than 94% of the area cultivated with sugarcane, almost 99% of pineapple, 83% of coffee, and 49% of green coconut (EMATER, 2014). In the northern region, Campos dos Goytacazes, São Francisco do Itabapoana, and Quissamã stand out producing sugarcane, pineapple, and green coconut. In the northwestern region, Porciúncula, Varre-sai, and Bom Jesus do Itabapoana stood out in growing coffee, corn, and sugarcane (EMATER, 2014). These crops could easily absorb all sewage sludge generated in the great cities of the region, such as Campos dos Goytacazes, Macaé, and Itaperuna since they have vast agricultural areas cultivated with species suitable for sewage sludge fertilization.

Some studies have demonstrated the advantages of fertilizing these crops with sewage sludge, such as improved soil quality, productivity gains, less dependence on chemical fertilizers, lower production costs, among others (CHIBA et al., 2009; FRANCO et al., 2010; JUNIO et al., 2013; MAIA, 2013; MARTINS et al., 2005; YADA et al., 2015). Sewage sludge recycling in these agricultural areas can represent considerable savings with chemical fertilizers, providing economic, environmental, and social benefits. Chiba et al. (2008) and Franco et al. (2010) analyzed the efficiency of sewage sludge in sugarcane fertilization and concluded

that sludge can supply up to 100% of nitrogen fertilizer requirement. Since sugarcane is the main agricultural crop in Rio de Janeiro State, the use of sewage sludge as fertilizer should be treated as a strategic issue for the agricultural sector of Rio de Janeiro.

Another traditionally agricultural region is the Mountain Region, which is recognized as a large producer of vegetables and responsible for more than 90% of lettuce production in the state (EMATER, 2014). Among the eight crops analyzed that are apt to receive sewage sludge, banana, coffee, tomato, and corn stand out in this region, with a total area of approximately 6,390 ha (EMATER, 2014). In addition to these crops, producers who practice fallow farming in this region could also use sewage sludge.

The fallow system can be defined as a form of agriculture marked by crop rotation of small areas for short periods (2 to 4 years) alternated with long periods of rest (5 to 10 years), showing a great historical and cultural representation in the Mountain Region of Rio de Janeiro (SILVA, 1996). In this system, the fallow time has an influence on environmental sustainability and economic viability because long periods of fallow to recuperate soil fertility can make the system unfeasible since it would require larger production areas, increasing the costs related to land clearing (CORREIA et al., 2004). Sewage sludge could be applied at the end of production cycle as a soil amendment, accelerating the recovery of soil chemical and physical characteristics during the fallow period, mainly organic matter, which is considered as one of the main quality indicators in this system (BENITES et al., 2010). With a less fallow time, production area can be optimized without the need to suppress new forest areas. According to legislation, soils that received sewage can be cultivated with any crop after 48 months. Thus, considering that fallow time varies from 5 to 10 years, there would be no restrictions on land use after this recovery period (BRASIL, 2006).

Metropolitan region of Rio de Janeiro is extremely important for agricultural recycling of sewage sludge since it has the highest population density of the state and hence it presents the greatest potential for sewage sludge generation. Among the eight crops analyzed, banana and orange cultivation stand out mainly in Itaguaí, Paracambi, Seropédica, Tanguá, and Rio Bonito (EMATER, 2014), being located less than 90 km from Rio de Janeiro City and having together more than 6,000 ha cultivated with only banana and orange, presenting a great potential for agricultural recycling of sewage sludge generated in this metropolis. Sewage sludge recycling in these areas could bring benefits for both sanitation companies, which would reduce their disposal costs and dispose of their residues in a more sustainable way, and producers, who could increase their production and reduce input costs. Bittencourt et al. (2014) analyzed, from 2007 to 2010, the agricultural recycling of sewage sludge in Paraná State in more than 2200 hectares of agricultural areas and concluded that the 80 producers participating in the recycling program saved an average of US\$ 813.45 ha⁻¹ in fertilizers and soil amendments.

In the coastal lowland regions, Araruama, Silva Jardim, Cabo Frio, and Saquarema are important producers of orange, banana, sugarcane, and green coconut, the main crops of the region, with a total area of 8,746 ha (EMATER, 2014). Costa Verde region has a prominent role in the banana production, mainly in Mangaratiba, which accounts for almost 33% of the area cultivated with bananas in the state. Both regions could use in agricultural areas the sludge generated in their cities and that from the metropolitan region of Rio de Janeiro, close to them.

South central and middle Paraíba River regions have already been large agricultural producers, mainly during the coffee cycle, but currently have only 2.12% of the agricultural area cultivated in Rio de Janeiro State (EMATER, 2014). In the south central region, tomato is the largest crop cultivated

in Paty do Alferes and Vassouras. In the middle Paraíba River region, banana stands out in Pirai and sugarcane in Rio Claro and Valença. Larger cities, but without large agricultural areas such as Resende and Volta Redonda, could use sewage sludge recycling in partnership with smaller cities, which have larger agricultural areas but do not generate large amounts of sludge.

In addition to economic benefits, agricultural recycling of sewage sludge also brings environmental advantages such as the mitigation of greenhouse gases by reducing chemical fertilizers and increasing soil carbon stock, as well as increase of soil biological diversity, reuse of nutrients (mainly N and P), and reduction residue disposal in landfills, increasing their useful life (LOZADA et al., 2015; OUIOMET et al., 2015). In order to guarantee these environmental benefits, the locational restrictions contained in the Article 15 of CONAMA Resolution No. 375/2006 must be respected, thus minimizing the risks to the environment and human health (BRASIL, 2006). In this sense, more in-depth studies are needed aiming at spatially demarcating apt areas for sewage sludge application and identifying the use and occupation of soil in these areas, which would bring more data to subsidize the recycling programs.

Conclusions

The analyzed sludge presented a high content of nutrients and organic matter and was included in the parameters of heavy metals, pathogenic agents, and bacteriological indicators stipulated by CONAMA Resolution No. 375/2006. All sludge samples were classified as class A, with favorable attributes for agricultural recycling.

The agricultural panorama of Rio de Janeiro State is favorable for agricultural recycling of sewage sludge with a great potential demand. Furthermore, among the 10 agricultural crops with the largest cultivated area in the state, sludge can be used as fertilizer or soil amendment in eight of them. The implementation of a State Sewage Sludge

Recycling Program could dispose of this material in a more sustainable way, as well as improve the quality of agricultural soils and reduce costs with chemical fertilizers, bringing about positive results for sanitation companies and producers.

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