International Journal of Recycling of Organic Waste in Agriculture (2021)10: 379-395
Doi: 10.30486/IJROWA.2021.1901014.1083

ORIGINAL RESEARCH

Characterization of composted organic solid fertilizer and fermented liquid fertilizer produced from the urban organic solid waste in Paipa, Boyacá, Colombia

José Francisco García Molano[1*], Joel David Parra Alba[1], Luis Alexander Páez Guevara[2]

Received: 10 June 2020 / Accepted: 03 July 2021 / Published online: 06 November 2021

Abstract

Purpose Urban organic solid waste (UOSW) has great potential to be transformed into solid and liquid organic fertilizers, thus avoiding its accumulation in landfills and reducing the environmental impact caused by the generation of gases and leachates. Therefore, the purpose of this research was to study the management of the UOSW in the municipality of Paipa as raw material for obtaining solid organic fertilizer through composting and a liquid fertilizer through fermentation.

Method The UOSW of Paipa was combined with inorganic salts such as carbonates, phosphates, sulfates and source of carbohydrates to enrich its bacterial load and chemical composition. The content of essential nutrients that contribute to good soil-plant synergy, heavy metals and pathogenic microorganisms in the primary and final material were determined.

Results The experiment showed a high COO load, between 24-35%, and similar values in organic N content in the primary materials. Heavy metals were found below the minimum allowed by the CTS 5167 of 2011 for the organic solid residue, and no pathogenic microorganisms were found. Composting and fermentation processes improved the physical-chemical properties of the materials; however, the liquid mineral organic fertilizer did not comply with the established parameters, while the solid one was in compliance with the requirements.

Conclusion After a period of 4 months, the study showed that solid UOSW from the municipality of Paipa can be used as a potential source for producing organic fertilizers by adding nutrients in mineral forms, complying with the nutrient requirements for plants and soil feeding organisms.

Keywords Compost safety, Leachate fermentation, Urban organic waste, Fertilizer

Introduction

The soil organic matter corresponds to the smallest solid fraction, yet is the most dynamic, as it comes from plant and animal waste or microbial mass in a decomposition process that leads to mineralization and humification (Juma 1999). It decomposes aerobically or anaerobically where oxide-reduction reactions occur, and whose final product depends on this environment. During its decomposition, a part of C is returned to the atmosphere as CO_2, while another part is transformed into more simple compounds that are mineralized, humidified (Bridgham and Ye 2013) or stored in its own microbial structures (Llorente et al. 2008). In addition, organic solid waste contains approximately 70–80% water, depending on the source, so inadequate transformation processes may lead to problems of air, soil and water pollution.

Undoubtedly, the Urban Organic Solid Waste (UOSW) is an increasingly abundant source of external organic matter. Its management has become critical due to its excessive generation, as a consequence of production and consumption processes, population growth, increased demand of food as well as the expenditure on resources and services. As far as the environmental sanitation is concerned, the use of UOSW represents benefits ranging from reducing the use and consump-

✉ José Francisco García Molano
jgarcia@jdc.edu.co

[1] Facultad de Ciencias Agrarias y Ambientales, Grupo de Investigación en Abonos Orgánicos Fermentados (AOF), Tunja, Colombia
[2] Facultad de Ciencias Agrarias y Ambientales, Grupo de Investigación INPANTA, Tunja, Colombia

tion of raw materials, minimizing the amount of waste disposed of in sanitary landfills and reducing the flow of leachate in those landfills which would greatly minimize environmental impacts. Regarding usable waste, the Colombian legislation has established parameters concerning collection methods, selective transport as well as the characteristics of the classification and harnessing stations; however, it has not indicated the organic waste management methods; similarly, the mandatory nature of harnessing energy has not been established and is subject to the criteria of municipalities, conforming to what each one includes in its Solid Waste Integral Management Plan (SWIMP).

According to the DANE in Colombia (2018) approximately 1.58 tons of urban solid waste reaching the landfills were generated by households, for example, in Bogotá, at the Doña Juana landfill, 187,963.8 tons of waste were received per month. Likewise, at the Pirgua-Tunja sanitary landfill in 2018, 4,281.12 tons were generated monthly (Superintendency of Public Domiciliary Services 2018), from which at least 40.3% constitutes organic waste. In the case of Paipa municipality, 420 tons of solid urban waste (SUW) are collected monthly, and according to the record of monthly disposal in the municipality, this amount is characterized according to SWIMP as 44.51% organic, 36.12% recyclable and 19.37% not usable waste.

On the one hand, the physicochemical and microbiological analysis shows that the Paipa UOSW displays favorable characteristics, firstly, in relation to harnessing and obtaining alternative energy and, secondly, as a liquid fertilizer and solid fertilizer. On the other hand, knowledge of microbial populations, as well as organic and inorganic composition is required to assess a potential risk the people who handle waste are exposed to, taking into account that during the decomposition of organic waste, strong odors and polluting gases such as CH_4, CO_2, NH_4, H_2S, NO_3 and NO_2 are produced, which in combination with other gases contribute to the increase in the planet's temperature (Moreno and Moral 2008). Decomposing urban waste in open-air facilities may lead to this problem not only because of the gases released into the atmosphere but also because of a leachate that ends up polluting soil and water. Additionally, Zahrim et al. (2015) stated that based on the greenhouse gas reduction measurement composting option is preferred to incineration as a waste management option.

As a consequence, the purpose of this article is to analyze the management of UOSW as raw material for obtaining a solid organic fertilizer by composting, and a liquid fertilizer by fermentation, with the addition of micro-elements in the form of inorganic salts and a source of carbohydrates to enrich its chemical composition and bacterial load.

Materials and methods

Characterization of UOSW (Urban Organic Solid Waste)

The analysis of the UOSW management was commenced by establishing the chemical and microbiological composition of the solid and liquid raw materials, for which samples were taken directly from a compactor refuse collection lorry (Fig. 1). The liquid waste was collected in sterilized glass jars with 1000 cc capacity, without leaving an air chamber; these were then hermetically closed and transported in a thermal polystyrene refrigerator containing ice. Following that, the solid sample was placed on a dehydration platform. Next, 10 subsamples were collected in a plastic container and mixed until homogenized; 1 Kg was taken in a plastic bag with a hermetic seal and placed in a thermal polystyrene refrigerator which was then transported to the laboratory of the Molecular Studies Interdisciplinary Group (MSIG) at the University of Antioquia for the corresponding analyzes.

Analytical methods

Solid sample

In the raw and final materials obtained in the composting process a pH at 10% in water and electrical conductivity in the soluble extract in aqueous medium using a ratio of 1:200 were established. The moisture content was determined at 378.15 K for a time of 24 hours. The content of Cd, Cr, Ni and Pb was determined through Atomic Absorption (AA). The total oxidizable organic carbon content was obtained by titrimetric methods; the density was determined by gravimetry and the total organic nitrogen by the Kjeldahl method (AOAC official methods). The C/N proportion data was calculated using the abovementioned results. Additionally, ash and moisture content were measured by the gravimetric method. Microbiological tests corresponded to mesophiles, thermophiles, molds, yeasts, CFU/g *Enterobacteriaceae* and *Salmonella* presence per 25 g and nematodes and protozoa count per 100 g CTS 5167 (2011).

Fig. 1 Compactor refuse collection lorry employed in Paipa, Boyacá, Colombia

Liquid sample

For this product, electrical conductivity and pH tests were run using a potentiometric technique. Furthermore, total phosphorus was measured by spectrophotometry while total solids, total suspended solids, total dissolved solids, volatile solids and fixed solids were determined through gravimetric tests. BOD_5 was calculated with an OxiTop measurement technique and, finally, Chemical Oxygen Demand (COD) was determined by closed reflux CTS 5167 (2011).

Fermentation process

In the dehydration zone, the leachate generated from the solid material was collected by gravity in an underground tank with a capacity of 4 m^3, then it was passed through a tube to a fermentation tank, where sugarcane molasses was added at 3% as an energy source, in the same way Zn, Cu, Mn, Fe, K and H_3BO_3 sulfates were dissolved at 0,5% and $MgSO_4$ at 1%. The fermentation process of the liquid took 20 days, during which a supernatant of different colors appeared. It corresponded to the fungal microorganisms and bacteria that were not identified in this test. The fermented liquid samples were then put in sterilized 1000 cc glass bottles and packed, without leaving an air chamber, in a thermal polystyrene refrigerator with cooling gel. They were later taken to a laboratory to be analyzed.

Composting process

The material discharged in the dehydration area (Fig. 2) was turned around daily for 10 days until humidity was reduced to 50% in order to allow oxygen to enter, and subsequently increase the temperature. Following that, the material was transferred to the composting area where overturning occurred for a period of 40 days, during which time temperature and humidity monitoring was performed until both factors stabilized at room temperature and at 30% humidity. At this point, the pile was humidified by adding 20 L/t of pure leachate to reactivate the microbial activity and increase the temperature. Subsequently, it stabilized again at room temperature with tumbling repeated every three days for 15 days. Next, it was watered with a fermented liquid mineral fertilizer at a ratio of 20 L/t. Finally, the obtained solid was ground, sieved and $Ca_{10}(PO_4)_6F$ phosphoric rock and dolomite lime ($CaCO_3MgCO_3$) were added at a concentration of 5%. This was done to guarantee a mineralogical composition with the characteristics of an organic mineral fertilizer that contributes to the feeding of soil organisms and plant nutrition.

At this point of the process (65 days of composting), 10 subsamples were collected from the pile at different heights and depths and put in a plastic container. Then they were homogenized and a single sample was extracted in a plastic bag with a hermetic seal. It was placed in a thermal polystyrene refrigerator with cooling gel and, just like the raw material samples, was sent to the MSIG laboratory. The monitoring was carried out every 30 days for four months.

Having obtained the laboratory results, we proceeded to analyze them and make corresponding comparisons with other studies carried out. The product was evaluated in accordance with the mandatory requirements established by the Colombian Technical Standard CTS 5167 regarding products for the agricultural industry, organic products used as fertilizers or fertilizers and soil improvers or conditioners.

Fig. 2 Area used for the composting process in Paipa, Boyacá, Colombia

Results and discussion

Physicochemical and microbiological composition of organic solid and liquid waste

Leachate

Compositional characteristics of our leachate, raw material for a liquid organic fertilizer, coincide with those presented for leachates generated in open and closed composting facilities and are in the range of 30 to 74,000 mg/L for BOD_5 and 42,180 to 107,160 mg/L COD (Roy et al. 2018). In our study, BOD_5 of 4000 mg/L was obtained, which corresponds to a seriously polluted classification taking into account that it exceeds 120 mg/L. Moreover, COD of 74,700 mg/L was detected. Its parameter is located within Class 4 of contaminated fluids that are between 4,000-50,0000 mg/L (Esguerra 1989) and also corresponds to seriously contaminated fluids, considering that the value is >200 mg/L in accordance with what has been mentioned in some studies (Hammer and Hammer 2003; Wan et al. 2019). The high values of COD indicate the need to treat this waste in order to avoid possible damage to the environment (Hashemi and Khodabakhshi 2016) and to be able to use it as a liquid organic fertilizer. The content of oxidizable organic carbon (COO) was at 24.4%; this COO level may be related to the solid-liquid mass transfer processes caused by the hydrolysis of organic matter by enzymatic reactions, solubilization of organic and inorganic molecules and, finally, entrainment of particulate matter as mentioned by Krogmann and Woyczechowski (2000).

The value of CE calculated in this study was low (Table 1) considering that the values range from 14,2 to 826 µS/m as reported by Roy et al. (2018); this can be related to a low content of dissolved inorganic substances such as chlorine anions, nitrates, phosphates and some cations such as sodium, magnesium, calcium and iron (Mishra et al. 2014). Besides, the leachate presented a strongly acidic pH of 4,313, which is consistent with that reported by Mokhtarani et al. (2012). This pH value can be attributed to the presence of acid-forming organisms through fast decomposition of organic matter, and can be responsible of accumulation of organic acids such as acetic, propionic, butyric and other acids (Samaniego and Pedroza 2013; Mokhtarani et al. 2012). Additionally, our results are below the ranges mentioned by Chelliapan et al. (2020) which are between 5.8 and 8.5 for the leachate from landfills, which would point to a lower amount of organic matter available to be degraded.

The total P content in this study stood at 0.73%, higher than reported by Azeem (2015) that was 0.308% in restaurant and hotel waste, this P present in the liquid phase could originate from different decomposition processes of phosphate organic molecules such as chitins, phospholipids, nucleic acids, amino phosphates, among others (Turner et al. 2007). The difference in the results could be related to the diversity of organic matter present in each of the test samples.

Regarding the total organic N content that was 1.73%, it was higher than the value presented in the work of Azeem (2015), which was 1.15%; the difference could be associated with hydrolytic processes of protein peptide bonds, which are the main N source present in urban solid waste (Jokela et al. 2002). Additionally, the N content found in the Paipa UOSW is relatively equal to the cattle, goat, pig, rabbit and poultry manure; however, it is lower than the vegetable residues with a high content of N such as tomato, beetroot and radishes, which contain 2.0% of N on average (Muñoz 2000).

Finally, the results show that the leachate does not contain heavy metals or pathogenic microorganisms (Table 1), which suggests that under the conditions in which the leachate was formed, they did not favor the mobility of metals, taking into account that high concentrations of metals are favored at a low pH, by the presence of humic and fulvic molecules and the formation of organometallic complexes (Roy et al. 2018). Besides, a high population of mesophiles was observed, which according to Salazar (2014) may correspond to bacteria, mold, yeasts and actinomycetes. The population of thermophiles was smaller considering that it is a liquid compound and, finally, molds form the least numerous population. Taking into account these characteristics, it is believed that the leachate can be used as a raw material to prepare a liquid organic fertilizer through fermentation.

Organic solid waste

For the UOSW, 35.7% COO was obtained, which represents food supply for the composting organisms, and which stimulated the microbial growth involved in self-heating during the initial stage of the fermentation process (Danon et al. 2008), taking into consideration the fact that, theoretically, municipal waste is composed of carbohydrates (52%), lignin (20%), hydrogenated compounds (12%), lipids (3%) organic acids (2.5%) and other compounds (10%) (Porta et al. 2003) and, according to Blasco and Burbano (2015), the COO of the UOSW presented a lower value than that reported for plant residues such as wheat straw (46%), barley (58%), rice (42%), corn stubble (38%), legumes (41%), dried leaves (44%) and sawdust as well as equine (40%), goat (40%) and duck (38%) manure, respectively. However, the COO in the UOSW is found in a higher concentration than the data obtained from the studies of cattle, sheep, pig, rabbit, hen, turkey manure or plant material such as oat straw, vegetables and tubers. The difference can be related to the presence of polysaccharides such as cellulose and lignin which have low biodegradability due to their complex structure, and which form part of the compounds the UOSW.

As it can be seen in Table 1, an average of 1.67% of total organic N was obtained, being higher compared to animal manure and plant residues similar to that reported by Samaniego et al. (2017). According to the United States-Canadian Tables of Feed Composition (1982), the percentage of N could correspond to the mineralization processes of nitrogenous compounds such as amino acids, hexosamines, nucleic and ribonucleic acids due to the presence of purines and pyrimidines among other molecules, which result in the formation of NH_4^+ and NO_3^-, a reaction that is strongly influenced by the pH and process temperature. The C/N ratio was 21.4, which indicates a slow mineralization rate considering that the COO percentage greater than 35.1 delays decomposition. On the other hand, a porous material with the density of 1.28 g/cm^3 allows the entry of O_2 as the material loses humidity reported at 76.6% by draining the water. This helps to increase the temperature, which allows the presence of thermophilic microorganisms responsible for the degradation of polymers such as cellulose.

Table 1 Physico-chemical characteristics of the leachate and the UOSW

Analysis	Parameter	Units	Value	Value
Organoleptic	**State**		Liquid	Solid
	Color		Terracotta	Heterogeneous
	Texture		-	Heterogeneous
Physical - Chemical	**Cd**	ppm	Not Determined	N D
	CaO	%	-	-
	Cr	ppm	<0.02	<0.02
	MgO	%	-	-
	Ni	ppm	<0.003	8.5
	Pb	ppm	<0.01	2.8
	Ashes	%	-	15.5
	Total Organic Oxidizable Carbon	%	24.4	35.7
	Electrical conductivity (1 / 200)	dS / m	0.0025	-
	CRA	%	-	-
	Density (20°C)	g / cm^3	1.02	1.28
	Total phosphorus	%	0.73	-
	Humidity	%	-	76.6
	Total organic nitrogen	%	1.73	1.67
	pH (10%)	-	4.313	-
	Total solids	mg / L	73354	-
	Total Suspended solids	mg / L	17367	-
	Total dissolved solids	mg / L	55987	-
	Volatile solids	ST%	71.4	-
	Fixed solids	ST%	28.6	-
	BOD_5	mg / L	4000	-
	Total COD	mg / L	74700	-
	C / N ratio	-	-	21.4
Microbiological	**Mesophilic**	c.f.u / g	3.0E+09	1.7E+09
	Thermophiles	c.f.u / g	1.0E+06	1.0E+06
	Molds	c.f.u / g	1.0E+03	0.0E+00
	Yeasts	c.f.u / g	0.0E+00	3.5+04
	Nematodes and/or protozoa		Absent	Absent
	Enterobacteria	c.f.u / g	0.00E+00	0.00E+00
	Salmonella	g 25	Absent	Absent

Compared to the leachate, the solid material does contain trace quantities of metals such as Cd, Cr, Ni and Pb that are below the minimum allowed by CTS 5167 of 2011. Although a high population of mesophilic microorganisms was found, followed by thermophiles, according to Álvarez (2010) these will likely be fungi from the Actinomycetes group (*Micromonospora, Streptomyces* and *Actinomyces*) that are characteristic of this type of material since they intervene in the degradation of organic matter such as cellulose and lignin, even though it must not be forgotten that populations change according to the percentage of humidity, temperature, pH, and oxygenation level. Finally, the presence of pathogenic bacteria such as *Enterobacteriaceae* and *Salmonella* was not detected.

Physicochemical and microbiological composition of the organic mineral solid and liquid fertilizer

Liquid fertilizer

Table 2 shows the results obtained within the analyzed parameters for four different samples of the final product: sample 1 with the addition of 3% molasses and samples 2, 3 and 4 with the addition of minerals and molasses. It has been observed, for example, that the COO in sample 1 has the lowest value, 18.1%, while for the others it is between 28.6% to 35.8% after 20 days of fermentation; which may be associated with inhibition processes due to the addition of sulfate-type mineral salts, which can affect the growth of microorganism populations and, additionally, affect metabolic processes as reported by Lin (1993) who found that the presence of metals such as Cu, Zn and Pb can inhibit acidogenic organisms (Table 3). Therefore, it can be observed that the larger the population of microorganisms, the lesser the amount of COO.

However, in compounds that contain COO, C is an energy source and N is used by the microorganisms present there for the formation of new cells, proteins and reproduction (Garcia et al. 2009; Wang et al. 2012), which is consistent with the percentage of total N that is lower in the Organic Liquid Fertilizer (OLF) where the populations of microorganisms are larger, and higher in Liquid Mineral Organic Fertilizer (LMOF) where the populations are lower. According to the study, the total nitrogen (TN) values were higher for the LMOF than for the OLF perhaps due to the higher pH (5.52) of the OLF that could have affected the balance between the ammonium ion (NH_4^+) and ammonia (NH_3) by converting non-volatile ammonium ions into volatile ammonia. Nevertheless, a lower amount of TN was also observed in sample 1, in relation to the samples treated with minerals. This could also be associated with the increase of thermophilic microorganisms in higher temperature, causing alterations in the NH_4^+-NH_3 balance (Pagans et al. 2005).

According to the report of Granada and Prada (2015) for agro-ecological and conventional compost leachates, the total nitrogen (TN) values are lower than those from the Paipa` UOSW, with and without minerals. The differences between these results could be related to the pH values or the biochemical composition of the different organic wastes present in the residue. However, both the agro-ecological leachates and the UOSW are within the range for foliar fertilizers, as a pH between 3.5-5.5 allows the cations solubility, while a pH greater than 5.5 makes cations reaction with the hydroxides and the elements precipitate (Li et al. 2018).

The content of P in the OLF and LMOF is very low and it presented a minor decrease in samples 1, 2 and 3 during the fermentation process, which can be attributed to the consumption of P by the microorganisms in order to obtain energy during the degradation of organic material, similar behavior to the one observed in the agro-ecological and conventional leachate in which phosphoric rock was added as a source of P; however, the reports were then 0.17-0.27 g/L, respectively. When comparing the P content in other liquid fertilizers such as that reported by Peralta et al. (2016) obtained through the fermentation of bovine manure and sugar cane molasses, with the addition of a microorganism consortium, it was observed that the total amount of phosphorus doubled to 0.74 g/L. The P was surely released by lactic acid bacteria found in the manure and molasses. Otherwise, for the total P of the UOSW, the reported amount corresponds to the one that comes from the phosphate organic molecules, taking into account that this element was not added with mineral sources. According to the United States-Canadian Charts of Feed Composition (1982), all residues of animal and plant origin contain P, thus the LMOF and OLF may become food for the microbial populations of the fertilizer and the soil where it is applied, but these residues are not a source of P for plants.

Regarding K, the reported value in the OLF is low (Table 1), while in the LMOF it is higher due to the addition of sulfates; though the content of K_2O, based on the study done by Granada and Prada (2015), was 33.7 g/L, which is high in comparison to the liquid fertilizer of UOSW, which is surely because one of the sources is a banana stem that is considered rich in potassium. Similarly, the liquid fertilizer reported by Peralta et al. (2016) that has as a source of bovine manure, sugar cane molasses and lactic acid bacteria of the *Lactobacillus, Streptococcus* and *Bifidobacterium* genuspresented a value of 17.2 g/L, while it was lower in the study done by Torres et al. (2016), who reported 8.3 g/L in the liquid organic fertilizer obtained from the mixture of 75% vermicompost leachate (whose substrate consisted of 10% coffee parchment an 10% chopped Cambur stem) and 25% Leonardite. Consequently, it can be observed that an important source of potassium corresponds to organic compounds, since the contribution of K_2SO_4 increases this element by only 5.10 g/L in the LMOF. However, this product does not comply with the requirements of the Colombian Technical Standard (CTS) for liquid mineral fertilizers, taking into account that it requires at least 40 g/L of TN, P_2O_5 and K_2O.

Regarding Ca, the value reported in the OLF is less than in the LMOF. This behavior can be associated with the addition of minerals such as, for example, $CaSO_4$. However, it is not rejected out that the reducing the populations of microorganisms where sulfates are added the consumption of phosphatic and Ca molecules decreases. On the other hand, when comparing with agro-ecological and conventional leachates, its content is greater than 0.42 and 0.62 g/L, respectively; while both the liquid fertilizers from bovine manure with the addition of lactic acid bacteria and the one obtained with vermicomposting show 5.2 and 4.5 g/L, correspondingly.

Equally, the behavior of Mg is similar to Ca, occurring in smaller amounts in the OLF than in the LMOF. The highest content is due to the fact that it is added as a sulfate; similarly, it is less than that reported in the agro-ecological leachate, 0.22 g/L and the conventional one, 0.47 g/L. In the case of the liquid fertilizer reported by Peralta et al. (2016), the content was 1.74 g/L, which is similar to the one presented by the LMOF, 1.95 g/L, while it is lower than the liquid fertilizer obtained from vermicompost, 3,79 g/L.

The elements Zn, Mn, Fe, Cu, presented different quantities in each of the samples, despite the fact that they were added in the same proportion. This behavior may be associated with different direct or indirect microorganism interactions with these metals, affecting their solubility (Li et al. 2018). In the sense, different pH values and a diversity in the chemical composition of the LMOF could be responsible for different values in the samples. When comparing agro-ecological, conventional leached products, manure with lactobacillus and vermicompost, in all cases a greater quantity of the mentioned elements has been observed due to the addition of sulfates and boric acid in a proportion of 0.5% of each of them.

It was observed that heavy metals are reported in quantities below 3 ppm; a value that is considered very low according to the parameters required by the CTS (See Appendix A.1), which made us realize that both OLF and LMOF as fertilizers are harmless with respect to these elements. This is why they can be used in food production; it is also important to bear in mind that these elements are consumed by plants in their metabolism in minimal quantities (Li et al. 2018; Stroppa et al. 2020).

Table 3 shows that there is no record of yeasts, nematodes, protozoa, *Enterobacteriaceae* or *Salmonella*, which indicates that they do not pose a biological risk. In this sense, Boucourt et al. (2006) mentioned that the fermentation processes decrease the levels of bacteria, for example fermentation of sugarcane with cattle manure decreases the levels of *E. coli* at 48 h and Sotil (2007) reports a reduction in the levels of total and fecal coliforms in the artisanal digestion of manure and organic matter, where initially a value of 10^7-10^8 MPN 100 mL^{-1} was determined and within a period of 61 days, it was reduced to 10^3 MPN 100 mL^{-1}. Equally, the same author reports that the greatest reduction in total and fecal coliforms occurred in the first 24 days, a period in which a pH decreased to 5.

Regarding the content of mesophiles and molds, it is higher in the OLF, while thermophiles represent a smaller amount. It could be said that this happens due to the consumption of biodegradable organic compounds, taking into account that growth factors constitute organic components that come from digestion of molecules of plant or animal origin such as vitamins, enzymes, antibiotics, phenol esters, toxins, some amino acids, unsaturated fatty acids, among others supplied in low concentration, which are not synthesized or metabolized by cells but incorporated into cellular structures and into specific metabolic function (Golueke 1992).

However, mesophiles, thermophiles and molds are present in the fertilizer without the addition of sulfates, while the product with added sulfates does not report molds. It should be noted that mesophiles were considerably reduced by the existence of sulfates, but thermophiles increased in two of the samples. This could be attributed to the presence of additives such as sulfates and sugar cane molasses that can affect temperature profiles and stimulate microbial activity, resulting in an earlier start and longer duration of the thermophilic phase compared to the OLF (Chen et al. 2010).

The addition of an easily assimilated carbon source (sugar cane molasses at 3%) allowed the proliferation of

Table 2 Physio-chemical composition of the organic and mineral liquid fertilizer

Parameter	Units	Value	Value	Value	Value	Average Value for samples 2, 3 and 4
SC		**Sample 1**	**Sample 2**	**Sample 3**	**Sample 4**	
State	---	Liquid	Liquid	Liquid	Liquid	
Color		Brown	Brown	Brown	Brown	
TON	g / L	1.34	3.75	2.64	2.40	2.93
TP	g / L	0.35	0.30	0.12	0.88	0.43
CaO	g / L	1.821	3.878	6.300	3.500	4.56
MgO	g / L	0.109	1.414	2.112	2.310	1.95
K_2O	g / L	0.637	4.910	6.270	4.130	5.10
Na	g / L	0.106	0.699	0.850	0.520	0.69
Zn	g / L	0.146	1.080	1.492	1.230	1.27
Cu	g / L	0.200	1.052	1.340	1.040	1.14
Fe	g / L	0.30	0.71	0.90	0.62	0.74
Mn	g / L	0.400	0.971	1.278	1.030	1.09
B	g / L	0.0006	0.0045	0.0098	0.0081	0.01
S	g / L	0.0030	0.0659	0.0059	0.0450	0.04
Total COO	g / L	18.1	35.8	28.6	28.6	31.00
C / N ratio	-	13.5	9.6	10.8	11.9	10.77
EC (1 / 200)	dS / m	4.41	3.75	5.17	4.46	4.45
Density (20 °C)	g / ml	1.01	1.00	1.02	1.05	1.02
TSS	g / L	88.60	22.00	29.00	23.00	24.67
pH (10%)	-	5.52	4.00	4.00	5.20	4.40

SC: Sample Code. TON: Total Organic Nitrogen. TP: Total Phosphorus. TSS: Total Suspended Solids

Table 3 Microorganisms present in the liquid mineral organic fertilizers

Parameter	Units	Value	Value	Value	Value	Average
SC		Sample 1	Sample 2	Sample 3	Sample 4	
Mesophiles	c.f.u/g	6.60E+08	1.10E+07	1.00E+06	2.00E+06	4.67E+06
Thermophiles	c.f.u/g	2.00E+03	4.00E+06	5.00E+06	1.00E+06	3.33E+06
Molds	c.f.u/g	2.00E+03	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Yeasts	c.f.u/g	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Nematodes and/or Protozoa		Absent	Absent	Absent	Absent	0.00E+00
Enterobacteria	c.f.u/g	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Salmonella	g 25	Negative	Negative	Negative	Absent	0.00E+00

bacteria from the microbial consortium that was formed in the fermentation, which affected the pH decrease. According to Garcés et al. (2004), as in spontaneous lactic fermentation under anaerobic conditions, lactic acid bacteria ferment water-soluble carbohydrates, producing lactic acid and a minor quantity of acetic acid. As these acids are generated, the pH of the fermented material drops to the level that inhibits the presence of microorganisms inducing putrefaction.

Solid compost

During the study, four samples of the organic mineral solid fertilizer (OMSF) were analyzed. The results indicate that the average content of COO is 15.5% in the final product. This is due to the fact that organic molecules were mineralized due to decreased humidity during the process, reaching 11.64%, which allowed the entry of oxygen, temperature increase and the presence of thermophilic microorganisms (Charest et al. 2004) in an amount of 7.45E+07 c.f.u/g, as indicated in Table 4. Furthermore, it was observed that this variable decreased with respect to the initial, which corresponds to the maximum microbial activity, reflected in the highest values of temperature (Samaniego et al. 2017; Gavilanes et al. 2016). This behavior contributes to the loss of C in the form of CH_4 and CO_2.

The C/N ratio represents values that reveal a high mineralization rate of the compost. This ratio is lower than the mineralization of other composted products that, in general, should be between 20 and 30. A low C/N value of 8.95 on average, as in the case of the present study, points to the fact that the available carbon is fully used by microorganisms while excess nitrogen is released, mainly in ammonia form (Wang et al. 2012), which could be due to volatilization, immobilization and nitrification processes, as reported by Bustamante et al. (2008). For this reason, the OMSF from UOSW will act faster as a nutrient for plants and soil organisms since they carry out the decomposition of organic matter through oxidation; a route followed by mineralization that corresponds to the assimilation and immobilization processes; that means the incorporation of C, N, P and S in inorganic compounds assimilable by plants such as NH_4^+, HPO_4^{2-}, SO_4^{2-} and the organic ones such as starches, cellulose, sugars and organic acids, consumed by microorganisms. The samples have diverse contents of TN which is low in relation to the quantities that plants may require. Temperature loss and the alkaline pH of 8.4 on average (Bustamante et al. 2008) cause liberation of the NH_4^+ generating a strong ammoniacal odor (Pagans et al. 2005).

As for P, the values are similar, but as it was added as apatite in proportion 5% of the mineral, it has a concentration of 23%, which means that each ton of a solid fertilizer receives 11.5 Kg of P_2O_5, which results in a concentration of 1.15% as mineral contribution. However, depending on the P concentration, researchers have established the 20% rock phosphate as the maximum limit for addition to compost, since higher values could be toxic to microorganisms, decreasing the decomposition rate due to the presence of fluorine (Sánchez et al. 2017). Besides, the other part corresponds to organic P of the composted organic material that contains phospholipids and phytases which are mineralized by phosphate solubilizing microorganisms (Gaind 2014).

Ca in the form of oxide has been observed in greater quantity, as it was added as CaO and $CaCO_3$ in phosphoric rock and dolomite lime. It corresponds to 31 Kg/t, that is to say 3.1%, which indicates that the rest of the calcium comes from organic material; Mg, on the other hand, is 0.6% lower than the level required by the CTS 5167 whereas K is between 1.2 and 1.6%, coming mostly from organic material. This AOMS could contribute to the improvement of exchangeable potassium in different crops as reported by Bhattacharyya et al. (2007). Moreover, taking into account that it is added as K_2SO_4 to the liquid fertilizer with an average concentration of 0.5% and when adding the solid fertilizer in a proportion of 20 L/t, it presents a concentration of 0.1% of K sulfate.

In reference to the cation exchange capacity (CEC), it corresponds to a variable that complies with the minimum required by the CTS; however, it is low with respect to compost maturity, taking into account that this value for mature compost is 67 cmol kg^{-1}. The depolymerization caused by microbial activity, hydrolysis and temperature is expected to increase the CEC by generating negative charges due to the deprotonation of carboxylic and hydroxy-phenolic compounds. Conversely, the increase in the polymerization degree causes a considerable increase in the specific surface area of the “humic” macromolecules which can generate more negative charges, increasing this value.

Compost maturity is determined by the CEC/COO rate that indicates what percentage of organic matter is responsible for cation exchange, whose minimum must be 1.9 (Roig et al. 1988) for the UOSW compost. Then, as it is observed in Table 4, in the first two samples the rate is below the parameter and samples 3 and 4 do comply with it. Although the product does not have a high maturity rate, its pH, temperature and humidity are stabilized, maintaining its characteristics; for this reason, when it is applied to the soil, it becomes food for the organisms, since it is less constant than humus.

The humidity retention capacity in the case of the final product varies between 254.2-101.8% due to the material heterogeneity; however, it retains 100% of its weight in water. This occurs because humic substances which are formed in the compost are hydrophobic compounds surrounded by hydrophilic residues, which constitute a hydrophobic space through weak non-specific interactions (Perminova et al. 2005) where water is stored. Water molecules that occupy nanopores can form a constant network of hydrogen bonds in the structure of humic substances. As a result, when it is applied to soil, the water plant tolerance deficit is favored (Kunhi et al. 2012; Cihlář et al. 2014).

Regarding particle sizes, Table 4 shows that on average, particles > 2 mm constitute 46.22%, while the size < 2 mm has a higher percentage of 53.7; however, sample 2 contains 85% of particles < 2 mm while sample 3 reports a percentage of 71.1% of particles > 2 mm. The importance of the particle size consists in the fact that it allows a closer proximity of organic molecules with cations and clay charges, favoring the formation of soil aggregates increasing their size (Charest et al. 2004; Bello et al. 2016).

Table 5 shows abundant populations of mesophilic, thermophilic and mold microorganisms. It is surely due to the fact that the initial microbiota of the materials to be composted is highly variable, depending on the substrate and the conditions in which it is preserved (Moreno and Moral 2008). On the other hand, according to Rickeboer et al. (2003), few mesophilic microorganisms and a high quantity of thermophiles were found in domestic organic waste, differing from what was reported in this study.

Table 4 Physico-chemical composition of the organic solid mineral fertilizer

Parameter	Units	Value	Value	Value	Value	Average
SC		Sample 1	Sample 2	Sample 3	Sample 4	
State		Solid	Solid	Solid	Solid	--------
Color		Brown	Brown	Brown	Brown	
Texture		C. Htg	C. Htg	C. Htg	C. Htg	
TON	%	1.82	1.73	1.97	2.03	1.8875
TP	%	1.75	2.45	1.99	1.78	1.9920
CaO	%	8.90	11.20	10.66	10.59	10.3372
MgO	%	0.529	0.687	0.666	0.872	0.6885
K2O	%	1.233	1.403	1.563	1.690	1.4722
Na	%	0.259	0.301	0.294	0.284	0.2846
Zn	%	0.00883	0.01440	0.01223	0.01600	0.0128
Cu	%	0.00318	0.00400	0.00200	0.00300	0.0030
Fe	%	0.1109	0.1800	0.1300	0.1210	0.1354
Mn	%	0.0400	0.1052	0.0520	0.1000	0.0743
B	%	0.0017	0.0018	0.0015	0.0011	0.00152
S	%	0.125	0.085	0.130	0.092	0.1080
Ashes	%	51.1	56.3	60.1	57.6	56.2750
C / N ratio	-	8.9	10.8	7.5	8.6	8.9500
CEC	mEq / 100 g	20.8	21.3	31.7	33.8	26.9000
CEC / CO	mEq / g CO	1.29	1.56	2.13	1.93	1.7252
Total COO	%	16.2	13.7	14.9	17.5	15.5750
EC (1 / 200)	dS / m	0.72	0.98	0.39	0.52	0.65250
CRA	%	156.3	109.8	254.2	101.8	155.5250
Density (20 °C)	g / cm^3	0.43	0.69	0.41	0.50	0.507500
Humidity	%	8.12	8.25	17.6	12.6	11.6425
pH (10%)	-	8.06	7.90	8.89	9.05	8.4750
Dry particle size	% dry mass > 2 mm	44.9	14.5	71.1	54.4	46.2250
Dry particle size	% dry mass < 2 mm	55.1	85.5	28.9	45.6	53.7750

SC: sample code. TON: Total Organic Nitrogen. TP: Total Phosphorus. C Htg: coarse heterogeneous

In this sense, the record of detected microorganisms in different composting processes, using techniques that involve cultivation, included a total of 155 different species of bacteria, 33 of those were actinomycetes, belonging to 66 different genus, and 408 species of fungi included in 160 different genus (Ryckeboer et al. 2003). The diversity of organisms in this type of material allows the presence of cellulolytic, amylolytic, phosphate solubilizers and proteolytic enzymes (Garcia 2006). This data makes it difficult to generalize a pattern of microbial diversity for composting. However, it is assumed that the knowledge of the composting microbiota is still limited, since even the results obtained by applying the most advanced molecular techniques do not report the total microbial populations associated with the composting process (Schloss et al. 2005).

Table 5 Microorganisms of the solid mineral organic fertilizer

Parameter	Units	Value	Value	Value	Value	Average
Mesophiles	c.f.u /g	1.10E+10	4.70E+09	4.40E+07	9.00E+06	3.94E+09
Thermophiles	c.f.u /g	9.40E+07	2.00E+08	1.00E+06	3.00E+06	7.45E+07
Molds	c.f.u /g	1.60E+06	1.10E+06	1.30E+04	3.20E+04	6.86E+05
Yeasts	c.f.u /g	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Nematodes and / or protozoa		Absent	Absent	Absent	Absent	0.00E+00
Enterobacteria	c.f.u /g	0	2.00E+02	1.00E+02	1.00E+02	1.00E+02
Salmonella	g 25	Negative	Negative	Negative	Negative	0.00E+00

According to the requirements for vegetables in nutrition, trace elements were labeled as heavy metals which are not frequently absorbed by plants, and which should not be present in fertilizers added to the soil (See Appendix A.2). It is observed that although these are present in the fertilizer, they are below the minimum required by the CTS and international standards. In this regard, the total concentration of heavy metals (Cd, Ni, Cr, Pb, among others) present in some organic residues increases during the mineralization of organic matter (Elvira et al. 1995). Though it can decrease due to the formation of insoluble complexes of elements with neo-formed humic acids and more polymerized organic fractions (Domínguez 2004).

With reference to the above, the As present 0.379 ppm on average where can reach the soil and transform into arsenate ($AsSO_4^{-3}$) and cannot intervene in glycolysis and use to decouple oxidation from phosphorylation that cannot occur without it. In the case of Cd with an average of 4.35 ppm from the added minerals, mainly associated with Zn, it is below the CTS average. One must bear in mind that it is very toxic to living beings because it reacts with the hydroxyl and carboxyl groups; however, some bacteria possess the expulsion mechanism of the cells, preventing their intoxication. It should be noted that Cr is the element with the highest proportion in the fertilizer, 28.35 ppm, which may be associated with the fact that this element is used in various agro-industrial processes, yet it can be reduced by the *Aeromonas, Bacillus, Clostridium, Desulfovibrio* and *Streptomyces* bacteria genus.

On the other hand, Pb that may come from fuels and whose content in the soil can be between 0.1-1 ppm, can be found in the fertilizer at an average of 13.63 ppm; which is lower than the amount allowed by the international standards, even though it can be methylated by bacteria genus such as: *Aeromonas, Alcaligenes, Flavobacterium* and *Pseudomonas*. Finally, Hg with a low presence of 0.00075 ppm can be used by the *Bacillus, Clostridium* and *Bacillus* and the *Aspergillus* and *Neurospora* fungi in their metabolism, reducing its concentration by volatilization or metallization through the Hg-reductase enzyme and the intervention of methylcobalamin coenzyme (Domínguez 2004). For the future study, phytotoxicity test is vital to conclude whether the compost is suitable or not as a soil conditioner (Zahrim et al. 2016).

Conclusion

The LMOF and OMSF do not pose any risk with regard to heavy metals or pathogenic microorganisms, which ensures soil safety where it is applied.

The CEC/COO shows that the maturity of the OMSF depends on the raw material used rather than on the composting time, considering that the minimum rate is 1.9 for UOSW.

The CEC of the OMSF presents a lot of variability, nonetheless, the minimum value complies with the required parameters and it may increase considering that the mineralization rate is high, allowing the release of H for the charges availability, which can improve this variable in the ground.

The liquid mineral organic fertilizer does not comply with the foliar or fertigation fertilizer requirements, specifically in the total organic nitrogen parameters P_2O_5 or K_2O, whose minimum content must be 15 g/L and the total of all the elements must not reach 40 g/L.

Acknowledgement The authors of this article express gratitude to the company “Red Vital” (Vital Net) in charge of the Public Services in Paipa for providing space, logistics and budget to carry out this research.

Compliance with ethical standards

Conflict of interest The authors declare that there are no conflicts of interest associated with this study.

Appendices

Appendix A.1 Heavy metals present in the organic liquid mineral fertilizers

Parameter	Units	Value	Value	Value	Value	Average
SC		**Sample 1**	**Sample 2**	**Sample 3**	**Sample 4**	
Cd	ppm	N. D	0.583	0.000	0.000	0.19
Cr	ppm	< 0.02	0	0.02	0.02	0.01
Ni	ppm	< 0.003	0.47	0.53	1.03	0.68
Pb	ppm	< 0.01	2.23	1.59	0.01	1.28
Hg	ppm	N. D	0	0	0	0.00
As	ppm	< 0.1	0.1	0.1	0.1	0.10

Appendix A.2 Heavy metals present in the organic solid mineral fertilizers

Parameter	Units	Value	Value	Value	Value	Average
SC		**Sample 1**	**Sample 2**	**Sample 3**	**Sample 4**	
Cd	ppm	17.400	0.003	0.003	0.003	4.35225
Cr	ppm	11.0	24.0	42.7	35.7	28.3500
Ni	ppm	13.8	12.0	12.4	21.11	14.8275
Pb	ppm	2.37	19.30	18.60	14.28	13.6375
Hg	ppm	0.01	0.01	0.01	0.00	0.00750
As	ppm	0.278	0.310	0.931	0.000	0.37975

References

Álvarez J (2010) Manual de compostaje para Agricultura Ecológica. Consejería de agricultura y pesca de la Junta de Andalucía. Espain. https://doi.3140/RG.2.2.20182.24647

Azeem S (2015) Liquid fertilizer from food waste-A sustainable approach. Int Res J Environ Sci 4: 8-15

Bello O, García F, Cuervo W (2016) Cuantificación de diazótrofos en la rizósfera del olivo (*Olea europaea* L.) cultivado en Boyacá, Colombia. Acta Agron 65: 109–115. https://doi.org/10.15446/acag.v65n2.44270

Bhattacharyya P, Chakrabarti K, Chakraborty A, Nayak DC, Tripathy S, Powell MA (2007) Municipal waste compost as an alternative to cattle manure for supplying potassium to lowland rice. Chemosphere 66: 1789-93. https://doi.org/10.1016/j.chemosphere.2006.07.062

Blasco M, Burbano H (2015) La vida en el suelo: Notas sobre su bioquímica y microbiología. Impresos la Castellana of Pasto, Colombia

Boucourt E, Carrasco E, López A, Rodriguez Z, Gutiérrez O (2006) Microbiota aerobia en caña fermentada con excreta vacuna como alternativa alimentaria. Revista Cubana de Ciencia Agricola 40: 279–282. https://www.redalyc.org/articulo.oa?id=193017723003

Bridgham SD, Ye R (2013) Organic matter mineralization and decomposition. In: DeLaune R.D, Reddy KR, Richardson CJ, Megonigal JP (ed) Methods in biogeochemistry of wetlands, 1st edn, SSSA Book Series, SSSAJ, USA, pp, 386-406. https://doi.org/10.2136/sssabookser10.c20

Bustamante MA, Paredes C, Marhuenda FC, Pérez A, Bernal MP, Moral R (2008) Co-composting of distillery wastes with animal manures: Carbon and nitrogen transformations in the evaluation of compost stability. Chemosphere 72: 551-7. https://doi.org/0.1016/j.chemosphere.2008.03.030

Charest MH, Antoun H, Beauchamp CJ (2004) Dynamics of water-soluble carbon substances and microbial populations during the composting of de-inking paper sludge. Bioresour Technol 91: 53–67. https://doi.org/10.1016/S0960-8524(03)00155-X

Chelliapan S, Arumugam N, Fadhil Md D, Kamyab H, Ebrahimi SS (2020) In: Singh L, Yousuf A, Mahapatra D (ed) Bioreactors: Sustainable design and industrial applications in mitigation of GHG emissions, 1st Edn, Elsevier, USA, 175-193. https://doi.org/10.1016/B978-0-12-821264-6.00011-5

Chen YX, Huang XD, Han ZY, Huang X, Hu B, Shi DZ, Wu WX (2010) Effects of bamboo charcoal and bamboo vinegar on nitrogen conservation and heavy metals immobility during pig manure composting. Chemosphere 78: 1177–1181. https://doi.org/10.1016/j.chemosphere.2009.12.029

Cihlář Z, Vojtová L, Conte P, Nasir S, Kučerík J (2014) Hydration and water holding properties of cross-linked lignite humic acids. Geoderma 230–231: 151–160. https://doi.org/10.1016/j.geoderma.2014.04.018

DANE (2018) Cuenta Satélite Ambiental y Económica de Flujo de Materiales - Residuos Sólidos. https://www.dane.gov.co/files/investigaciones/pib/ambientales/cuentas_ambientales/cuentas-residuos/Bt-Cuenta-residuos-2016p. Accessed 18 June 2007

Danon M, Franke-Whittle I, Insam H, Chen Y, Hadar Y (2008) Molecular analysis of bacterial community succession during prolonged compost curing. FEMS Microbiol. Ecol 65: 133–144. https://doi.org/10.1111/j.1574-6941.2008.00506.x

Domínguez J (2004) State-of-the-art and new perspectives on vermicomposting research. Earthworm Ecology 401–424. https://doi.org/10.1201/9781420039719.ch20

Elvira C, Mato S, Nogales R (1995) Changes in heavy metal extractability and organic matter fractions after vermicomposting of sludges from a paper mill industry and wastewater treatment plant. Fresenius Environ Bull 4: 503-507

Esguerra M (1989) Experiencias prácticas con biodigestores de bajo costo para la generación de energía y el tratamiento de aguas residuales en países en desarrollo. Conferencia Internacional de Mecanización Agraria. Seminario FAO-CNRE: Tecnologías de producción de biogás, Espain

Gaind S (2014) Effect of fungal consortium and animal manure amendments on phosphorus fractions of paddy-straw compost. Int Biodeterior Biodegradation 94: 90-97. https://doi.org/10.1016/j.ibiod.2014.06.023

Garcés A, BerrioL, Ruiz S, Serna de León J, Builes A (2004) Ensilaje como fuente de alimentación para el ganado. Revista Lasallista de Investigación 1: 66–71. https://www.redalyc.org/articulo.oa?id=69511010

Garcia F (2006) Estructura Del Suelo y Nutrición Vegetal. Cultura Cientifica 4: 48–55. https://www.jdc.edu.co/revistas/index.php/Cult_cient/article/view/387

Garcia F, Gil P, Carrillo A (2009) Caracterización y calidad de un abono orgánico fermentado aof preparado con residuos del proceso de industrialización de la papa (*Solanum tuberosum L*). Logos C and T 1: 68–80. https://doi.org/10.22335/rlct.v1i1.35

Gavilanes I, Samaniego J, Idrovo J, Bustamante MA, Moral R, Paredes C (2016) Windrow composting as horticultural waste management strategy - A case study in Ecuador. Waste Manag 48: 127-134. https://doi.org/10.1016/j.wasman.2015.11.026

Golueke CG (1992) Bacteriology of composting. Biocycle 33: 55–57

Granada A, Prada Y (2015) Caracterización del lixiviado agroecológico a partir de residuos orgánicos de cultivos. RIAA 6: 169-182. https://doi.org/10.22490/21456453.1414

Hammer MJ, Hammer MJr (2003) Water and wastewater technology. Prentice-Hall of India, New Delhi

Hashemi H, Khodabakhshi A (2016) Complete treatment of compost leachate using integrated biological and membrane filtration processes. IJCCE 35: 81-87. https://doi.org/10.30492/IJCCE.2016.23589

Jokela J, Kettunen R, Sormunen K, Rintala J (2002) Biological nitrogen removal from municipal landfill leachate: Low-cost nitrification in biofilters and laboratory scale in-situ denitrification. Water Res 36: 4079–4087. https://doi.org/10.1016/S0043-1354(02)00129-X

Juma NG (1999) The pedosphere and its dynamics. A systems approach to soil science. Volume 1: Introduction to soil science and soil science resources. Salman Productions 315. https://doi.org/10.1016/s0016-7061(01)00014-3

Krogmann U, Woyczechowski H (2000) Selected characteristics of leachate, condensate and runoff released during composting of biogenic waste. Waste Manag Res 18: 235–248. https://doi.org/10.1007/s11157-018-9462-5

Kunhi Y, Kučerík J, Diehl D, Schaumann G (2012) Cation-mediated cross-linking in natural organic matter: A review. Rev Environ Sci Biotechnol 11: 41–54. https://doi.org/10.1007/s11157-011-9258-3

Li Z, Wang P, Menzies, Menzies NW, Kopittke PM (2018) Defining appropriate methods for studying toxicities of trace metals in nutrient solutions. Ecotoxicol Environ Saf 147: 872–880. https://doi.org/10.1016/j.ecoenv.2017.09.044

Lin CY (1993) Effect of heavy metals on acidogenesis in anaerobic digestion. Wat res 27: 147-152. https://doi.org/10.1016/0043-1354(93)90205-V

Llorente M, Lafuente F, Ruipérez C, Turrión M (2008) Uso de parametros edáficos como indicadores del efecto del uso del suelo en el páramo Calizo Castellano-Leonés. SECF 25: 273–279

Mishra S, Lata A, Tiwary D (2014) Studies of physico-chemical status of the ponds at Varanasi holy city under anthropogenic influences. IJERD 4: 261–268

Mokhtarani N, Bayatfard A, Mokhtarani B (2012) Full scale performance of compost's leachate treatment by biological anaerobic reactors. Waste Manag Res 30: 524–529. https://doi.org/10.1177/0734242X11411014

Moreno J, Moral S (2008) Compostaje. Mundi-Prensa, Espain

Muñoz J (2000) Compostaje en Pescador, Cauca: Tecnología apropiada para el manejo de residuos orgánicos y su contribución a la solución de problemas medioambientales. Universidad Nacional de Colombia, Colombia

Pagans E, Barrena R, Font X, Sánchez A (2005) Ammonia emissions from the composting of different organic wastes. Dependency on process temperature. Chemosphere 62: 1534–42. https://doi.org/10.1016/j.chemosphere.2005.06.044

Peralta L, Juscamaita J, Meza V (2016) Obtaining and characterising an organic liquid fertilizer due to the treatment of dairy farm cattle manure using a lactic acid microbial consortium. Ecología Aplicada 15: 1–10. https://doi.org/10.21704/rea.v15i1.577

Perminova V, Kovalenko N, Kopplin S, Hatfield K, Hertkorn N, Belyaeva Y, Petrosyan S (2005) Design of quinonoid-enriched humic materials with enhanced redox properties. Environ. Sci Technol 39: 8518–8524. https://doi.org/10.1021/es050915j

Porta J, Lopez M, Roquero C (2003) Edafologia para la agricultura y el medio ambiente. Mundi-Prensa, Espain

Roig A, Lax A, Cegarra J, Costa F, Hernandez MT (1988). Cation exchange capacity as a parameter for measuring the humification degree of manures. Soil Sci 146: 311–316. https://doi.org/10.1097/00010694-198811000-00003

Roy D, Azaïs A, Benkaraache S, Drogui P, Tyagi R (2018) Composting leachate: Characterization, treatment, and future perspectives. Rev Environ Sci Biotechnol 17: 323–349. https://doi.org/10.1007/s11157-018-9462-5

Ryckeboer J, Mergaert J, Vaes K, Klammer S, De Clercq D, Coosemans J, Insam H, Swings J (2003) A survey of bacteria and fungi occurring during composting and self-heating processes. Ann Microbiol 53: 349–410. http://hdl.handle.net/1854/LU-218678

Salazar T (2014) Actividad microbiana en el proceso de compostaje aerobio de residuos sólidos orgánicos. RIU 3: 74–84. https://doi.org/10.17162/riu.v3i2.524

Samaniego J, Pedroza A (2013) Potential uses of volatile fatty acids in soil, water and air. Terra Latinoam 31: 155–163

Samaniego JJ, Pérez-Murcia MD, Bustamante MA, Paredes C, Pérez-Espinosa A, Gavilanes-Terán I, López M, Marhuenda-Egea FC, Brito H, Moral R (2017) Development of organic fertilizers from food market waste and urban gardening by composting in Ecuador. PLoS ONE 12: e0181621. https://doi.org/10.1371/ journal.pone.0181621

Sánchez O, Ospina DA, Montoya S (2017) Compost supplementation with nutrients and microorganisms in composting process. Waste Manag. 69: 136-153. https://doi.org/10.1016/j.wasman.2017.08.012

Schloss PD, Hay AG, Wilson DB, Gossett JM, Walker LP (2005) Quantifying bacterial population dynamics in compost using 16S rRNA gene probes. Appl Microbiol Biotechnol 66: 457–463. https://doi.org/10.1007/s00253-004-1727-y

Sotil F (2007) Dinámica poblacional de los microorganismos del grupo de coliforme, en el proceso de biodegradación aeróbica y anaeróbica de los abonos líquidos orgánicos biol y purin. Universidad Nacional Agraria La Molina, Perú

Stroppa N, Onelli E, Hejna M, Rossi N, Gagliardi A, Bini L, Baldi A, Moscatelli A (2020) Typha latifolia and Thelypteris palustris behavior in a pilot system for the refinement of livestock wastewaters: A case of study. Chemosphere 240: 124915. https://doi.org/10.1016/j.chemosphere.2019.124915

Superintendency of Public Domiciliary Services (2018) Final disposition of solid waste. National Report. https://www.superservicios.gov.co/sites/default/archivos/Publicaciones/Publicaciones/2020/Ene/informe_nacional_disposicion_final_2019. Accessed on 4 February 2020 (a). Comprehensive evaluation of providers servigenerales Tunja city S.A. E.S.P. IOP. https://www.superservicios.gov.co/sites/default/archivos/Acueducto%2C%20alcantarillado%20y%20aseo/Aseo/2018/Dic/evaluacion_integral_de_prestadores_servigenerales_ciudad_de_tunja_s.a._e.s.p. Accessed on 12 Novenber 2019 (b)

Torres D, Mendoza B, Marco L, Gómez C (2016) Calidad de abonos orgánicos empleados en la depresión de Quíbor-Venezuela bajo ambientes protegidos. Ciencia y Tecnología, 9: 1-10. https://doi.org/10.18779/cyt.v9i2.209

Turner L, Condron L, Richardson S, Peltzer D, Allison V (2007) Soil organic phosphorus transformations during pedogenesis. Ecosystems 10: 1166-1181. https://doi.org/10.1007/s10021-007-9086-z

United States-Canadian tables of feed composition (1982) Nutritional data for United States and Canadian feeds, Third revision. Washington, DC: The National Academies Press. https://doi.org/10.17226/1713

Wan H, Abdul K, Shazwani N, Sharil S, Mundher Z (2019) Spatial and temporal risk quotient based river assessment for water resources management. Environ. Pollut 248: 133–144.

https://doi.org/10.1016/j.envpol.2019.02.011

Wang L, Lv D, Yan B, Zhang Y (2012) Fluorescence characteristics of dissolved organic matter during composting at low carbon/nitrogen ratios. Waste Manag Res 31: 203–211. https://doi.org/10.1177/0734242X12468195

Zahrim Y, Asis T, Hashim M.A, Al-Mizi TMA, Ravindra P (2015) A review on the empty fruit bunch composting: Life cycle analysis and the effect of amendment(s). Advances in Bioprocess Technology, pp 1-13. https://sci-hub.tw/10.1007/978-3-319-17915-5_1

Zahrim Y, Leong P, Ayisah S, Janaun J, Chong K, Cooke F, Haywood S (2016) Composting paper and grass clippings with anaerobically treated palm oil mill effluent. Int J Recycl Org Waste Agricult 5: 221–230. https://doi.org/10.1007/s40093-016-0131-9