Research Paper

Mineralization of organic matter and productivity of tifton 85 grass (*Cynodon* spp.) in soil incorporated with stabilized sludge from a vertical flow constructed wetland

Diogo André P. Silva, Antonio T. Matos and Mateus P. Matos

ABSTRACT

Little is known regarding how to discard the sludge accumulated in vertical flow constructed wetlands (VF-CWs) and what the potential impacts could be. The objective of this paper was to evaluate the mineralization of organic matter (OM) in soil and productivity of tifton 85 grass (*Cynodon* spp.) after incorporating sludge collected at different depths from a VF-CW (used to treat septic tank sludge), to a tropical soil (Oxisol). Sludge samples were collected at depths of 0–5, 5–10 and 10–15 cm from a VF-CW that was used over a period of three years. The sludge collected at each depth was incorporated into the soil at a dose equivalent to 30 g m^{-2} year^{-1} of total nitrogen, and the experimental area was planted. During a period of 215 days, total and easily oxidizable carbon, total, ammonia, nitric and organic nitrogen in the residue-soil mixtures were analyzed. Based on the data obtained, the mineralization fractions (MF) were estimated for the specific monitoring period and annually considering first order and two-phase kinetic equations. The annual MF of the OM were higher than 96% and the sludge-amended soil resulted in an increase in grass yield.

Key words | mineralization fraction, organic matter decay, septic tank sludge

Diogo André P. Silva
Antonio T. Matos (corresponding author)
Belo Horizonte, MG,
Brazil
E-mail: *atmatos@desa.ufmg.br*

Mateus P. Matos
Lavras, MG,
Brazil

This article has been made Open Access thanks to the generous support of a global network of libraries as part of the Knowledge Unlatched Select initiative.

INTRODUCTION

There are several technologies for the treatment/disposal of sewage sludge; one such technique is a vertical flow constructed wetland (VF-CWs), also referred to as 'planted drying beds'. According to Suntti *et al.* (2011) and Andrade *et al.* (2017), planted VF-CWs are a natural and decentralized system for the treatment of anaerobic or aerobic sludge, with low implantation costs, operational simplicity, low energy consumption and they are appropriate for diverse situations, in addition to not requiring the addition of chemicals to perform dewatering. According to Stefanakis & Tsihrintzis (2012), the sewage sludge is applied superficially to a porous and planted substrate, where over time it is dehydrated, resulting in the accumulation of a dark-colored 'biosolid', which is rich in organic matter. However, for the system to function properly it is necessary that the accumulated organic matter be removed from time to time so the VF-CW can be used continuously, without interruptions to its operation.

As the most attractive alternative, the accumulated sludge removed from a VF-CW can be incorporated into the soil, because this material improves the chemical, physical and biological properties of soils, promotes an increase in agricultural productivity and reduces the costs of soil recovery (Ferrer *et al.* 2011). Agriculture has long recognized the benefits of waste materials as a

doi: 10.2166/washdev.2019.133

nutrient source and as an amendment to improve the physical and chemical properties of soils (Alvarenga *et al.* 2015).

The usual criteria for determining the annual application rate of sewage sludge in agricultural soils is based on the mineralization of this residue, mainly by evaluating the nitrogen availability (Doublet *et al.* 2010). The annual mineralization fraction of the sewage sludge therefore depends on the soil type into which it was incorporated, the treatment it underwent, and the rate at which it was applied (Parnaudeau *et al.* 2004).

The quantification of organic carbon and nitrogen mineralization can be obtained under field or climate-controlled conditions in the laboratory, which is easier to install and operate, but often disregards the infinity of physical, chemical and biological processes that influence the mineralization of organic matter in field conditions.

The dynamics of organic matter mineralization in soils have been commonly expressed by first-order chemical kinetic equations (Stanford & Smith 1972), as well as by the exponential two-phase model (Inobushi *et al.* 1985). However, there is little knowledge regarding mineralization and the fertilization potential of the sludge accumulated in VF-CWs. The objective of this study was therefore to evaluate the mineralization of organic matter in sludge and the productivity of tifton 85 grass (*Cynodon* spp.) after incorporating sewage sludge collected at different depths from a VF-CW, to a tropical soil (Oxisol).

METHODS

Sludge used in the field experiments was collected at the Center for Research and Training in Sanitation of the Federal University of Minas Gerais (CePTS-UFMG), located at the Wastewater Treatment Plant of the Arrudas River Basin (WWTP-Arrudas), in the municipality of Belo Horizonte, Minas Gerais, Brazil, at the geographic coordinates: 19°53′42″ S and 43°52′42″ W.

In this area, there are three vertical flow constructed wetlands (VF-CW), planted with tifton 85 grass (*Cynodon* spp.) and measuring 29.1 m^2 in area, with 0.7 m of support medium. One of the units was chosen to receive raw sludge, with a hydraulic loading rate (HLR) of 13.1 $m^3 m^{-2}$ per year and a solids loading rate (SLR) of 81 kgTS m^{-2} per year (Calderón-Vallejo *et al.* 2015).

The organic material under analysis was accumulated in a 15 cm layer after three years of disposal from a septic tank to the VF-CW which was planted with tifton 85 grass (*Cynodon* spp.). Organic material accumulated in the VF-CW (Figure 1(a)) was collected from the layers at 0–5, 5–10 and 10–15–cm (Figure 1(b)) at random spots throughout the bed and mixed to obtain a composite sample. The layers are represented by the acronyms: CWL 0–5, CWL 5–10 and CWL 10–15.

To characterize the organic residues collected on the VF-CW and the soil to which it was applied, pH was

Figure 1 | Panoramic view of the vertical flow constructed wetlands, receiver of sanitary sewage sludge from the septic tank and cultivated with tifton 85 grass (a), and detail of the profile of organic material accumulated on the substrate of the system, where samples were collected (b).

measured in a solution prepared with 0.01 mol L^{-1} calcium chloride; the easily oxidizable carbon (OOC) was quantified by the Walkley–Black method. Total nitrogen (TN) was quantified using the Kjeldahl method, the water content (WC_{wb}) was measured after oven drying at 65 °C. Total solids (TS) were quantified after oven drying at 105 °C, and total volatile solids (TVS) quantified after carbonization of dry matter in the muffle furnace at 550 °C, according to the methodology described in Matos (2015). Total organic carbon (TOC) was quantified using the Total Carbon Analyzer (TOC-V_{CPN}). Additional analyses were performed on the soil, including: phosphorus and potassium which were extracted with a Mehlich 1 solution and quantified by the spectrophotometer method; exchangeable calcium and magnesium (Ca + Mg) and aluminum (Al^{3+}) were extracted with a 1 mol KCl L^{-1} solution; potential acidity (H + Al) was extracted with a 0.5 mol L^{-1} calcium acetate solution and quantified by titration methods, and the soil granulometric composition was quantified using the pipette method (Matos 2015).

Table 1 presents the chemical and physical characterization of soil samples and organic residues accumulated at different depths in the VF-CW. Based on the results, it was verified that the soil to which the sludge was incorporated is clayey, which, from an agricultural point of view, has low available phosphorus, high available potassium, good Ca + Mg, very low exchangeable Al^{3+}, good pH and very low potential acidity (H + Al). Therefore, chemically there appears to be no restrictions on the activity of microorganisms to decompose the organic material.

With regards to the organic residues collected in the VF-CW, the OOC and TOC contents were lower in the deeper collection layers. These results corroborate the studies of Matamoros *et al.* (2012), who quantified a value of 52% for organic matter in the surface layer and 40% in the deep layer of a 0–130 cm profile in a VF-CW. This result indicated that the deeper the layer in relation to the surface, the more stabilized the accumulated organic material (Uggetti *et al.* 2012). From the observed OOC/TOC ratio, it was expected that mineralization of organic material from the residues incorporated to the soil would be low due to the presence of a smaller quantity of labile C (C-carbohydrates) and a higher presence of stable recalcitrant compounds.

An experiment was conducted to quantify organic matter mineralization of the organic residues collected in the VF-CW, and its potential as a fertilizer considering biomass

Table 1 | Chemical and physical characteristics of the soil (air dried fine earth) and the organic materials collected at the depths of 0–5 cm (CWL 0–5), 5–10 cm (CWL 5–10) and 10–15 cm (CWL 10–15) of the VF-CW

Soil			**Organic residues accumulated in the VF-CW**				
Variables	**Units**	**Values**	**Variables**	**Units**	**CWL 0–5**	**CWL 5–10**	**CWL 10–15**
pH^b	–	4.61	pH^b	–	5.2	5.8	5.5
OOC^a	(dag kg^{-1})^c	1.23	OOC^a	(dag kg^{-1})	15.75	10.05	9.45
TOC^a	(dag kg^{-1})	1.60	TOC^a	(dag kg^{-1})	27.84	18.33	15.99
TN^a	(dag kg^{-1})	0.13	OOC/TOC		0.57	0.55	0.59
K^{+a}	(mg dm^3)	141.0	TN^a	(dag kg^{-1})	2.17	1.26	1.24
Ca^{2+a}	($cmol_c$ dm^{-3})	2.29	C/N		9.4	10.4	9.9
P^a_{disp}	(mg dm^3)	2.4	WC^b_{wb}	(dag kg^{-1})	37.47	36.26	39.79
Al^{3+a}	($cmol_c$ dm^{-3})	0.10	TS^b	(dag kg^{-1})	61.45	62.86	59.47
$H + Al^a$	($cmol_c$ dm^{-3})	3.3	TVS^b	(dag kg^{-1})	38.63	25.64	22.84
$Clay^a$	(dag kg^{-1})	40.0					
$Silt^a$	(dag kg^{-1})	8.3					
$Sand^a$	(dag kg^{-1})	13.5					

OOC, easily oxidizable organic carbon; TOC, total organic carbon; TN, total nitrogen; K, potassium; Ca, calcium; P, phosphorus; Al, aluminum; H + Al, potential acidity; WC_{wb}, water content; TS, total solids; TVS, total volatile solids.
[a]quantified in relation to dry matter.
[b]quantified in relation to fresh matter.
[c]equivalent to mass/mass in percentage.

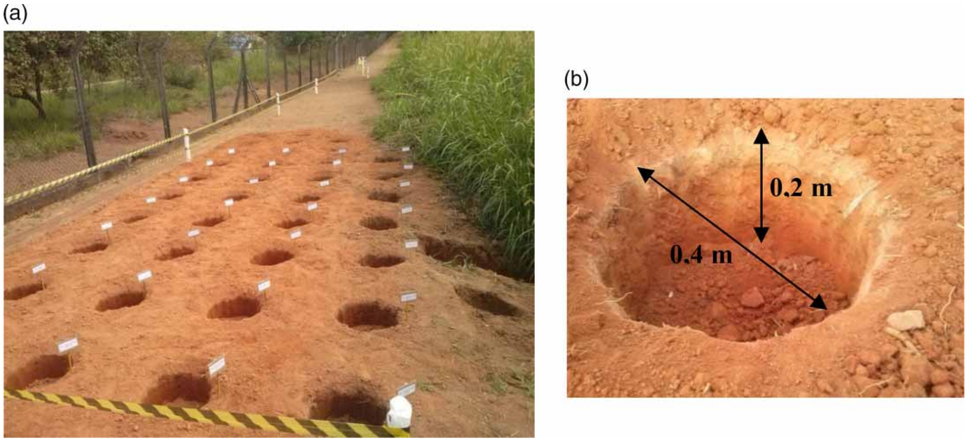

Figure 2 | Panoramic view of the holes formed to fill with soil material mixed with organic residues collected from the VF-CW (a) and detail of the hole dimensions (b).

productivity of tifton 85 shoots, under field conditions in an area of a tropical soil (Oxisol) at the Federal University of Minas Gerais – UFMG, Pampulha Campus, located in the municipality of Belo Horizonte – MG (coordinates 19°52′23.71″ S and 43°57′52.87″ W). In the experimental area, 32 cylindrical holes were dug (Figure 2(a)) measuring 40 cm in diameter and 20 cm in depth (Figure 2(b)), of which 16 were used to quantify organic matter mineralization and 16 to analyze the productivity of tifton 85 grass. The holes were filled with approximately 25 dm^3 of the mixture (soil removed from the area + organic residue), and in the control treatment the same soil was replaced. The experiment was set up in a completely randomized design (CRD), with three treatments and four replicates, installed in a split-plot design with treatments in the plots and assessment times in the sub-plots.

The quantities of organic residues added to each hole were calculated to provide 30 g m^{-2} of N, the recommended dose for pasture maintenance, considering 100% mineralization of the TN contained in the residues. The quantities (in relation to wet matter) of organic residue mixed with the soil were 2.27 g m^{-2} (286.0 g $hole^{-1}$) of CWL 0–5, 3.58 g m^{-2} (451 g $hole^{-1}$) of CWL 5–10 and 3.65 g m^{-2} (460.0 g $hole^{-1}$) of CWL 10–15, considering incorporation in a 20 cm layer with specific mass of 1.0 kg dm^{-3}. One week after incorporating the organic material into the soil, tifton 85 grass (*Cynodon* spp.) was planted by inserting 10 seedlings per experimental unit, which were irrigated every 15 days.

Field monitoring to evaluate the decay of organic carbon and nitrogen contents in the soil-residue mixture was initiated in June 2016 and completed in January 2017, with a total of nine collections of the organic residue-soil mixtures performed at 0, 1, 2, 5, 11, 23, 47, 100 and 215 days, in the entire profile of each hole to a depth of 20 cm, with the aid of a tubular sampler. In the samples, the contents of OOC, TOC, TN, $N_{Ammonia}$ and N_{Nitric}, as well as the water content (WC_{wb}), were quantified according to the methods described by Matos (2015). Organic nitrogen (ON) was calculated from the difference between TN and the sum of $N_{Ammonia}$ and N_{Nitric}. The soil temperature was monitored by means of measurements with a thermocouple-type digital thermometer inserted to a depth of 20 cm inside the holes.

To describe the mineralization of soil TOC, OOC and ON, the models used were the first order simple exponential model (Equation (1)) proposed by Stanford & Smith (1972), and the two-phase model (Equation (2)) proposed by Inobushi *et al.* (1985). The mineralization potentials and mineralization coefficients were obtained after adjustment of the mathematical models by non-linear regression using the program Sigma Plot 13.0.

$$M_{(\min)\mathrm{cal}} = M_{\mathrm{pot}}(1 - e^{-\mathrm{kt}}) \quad (1)$$

$$M'_{(\min)\mathrm{cal}} = M_{\mathrm{pot}(L)}.(1 - e^{-k(L).t}) + M_{\mathrm{pot}(R)}.(1 - e^{-k(R).t}) \quad (2)$$

where $M_{(\min)cal}$ and $M'_{(\min)cal}$ are the accumulated mineralized mass calculated for a given degradation time per unit mass of the soil-residue mixture (dag kg^{-1} or mg kg^{-1}); $M_{(pot)}$ is the potentially mineralizable mass per unit mass of the soil-residue mixture (dag kg^{-1} or mg kg^{-1}); k is the mineralization coefficient (d^{-1}); t is the monitoring time after incorporating the organic material into the soil (d); $M_{pot(L)}$ is the potentially mineralizable mass of the most labile fraction of the organic residue, per unit mass of the soil-residue mixture (dag kg^{-1} or mg kg^{-1}); $k(L)$ is the mineralization coefficient of the most labile fraction of the organic residue in the soil (d^{-1}); $M_{pot(R)}$ is the potentially mineralizable mass of the most recalcitrant fraction of the organic residue, per unit mass of the soil-residue mixture (dag kg^{-1} or mg kg^{-1}); and $k(R)$ is the mineralization coefficient of the most recalcitrant fraction of the organic residue in the soil (d^{-1}).

Although the accumulated mineralized masses were calculated using both Equations (1) and (2), the mineralization fraction of organic C and N was estimated using only the conceptual model (Equation (3)) and the parameters obtained in the two-phase model (Equation (4)):

$$MF_{(cal1)} = (M'_{(\min cal}/M_{(incorp)}).100 \quad (3)$$

$$MF_{(calc\,2)} = (M'_{(\min\ cal)}/M_{pot(L)} + M_{pot(R)}).100 \quad (4)$$

where $MF_{(cal\ 1)}$ and $MF_{(cal\ 2)}$ is the mineralization fraction of the selected variable (TOC, OOC, ON) at the degradation time of 215 days (%); $M_{(incorp)}$ is the mass applied to the soil (g kg^{-1}); and $M_{pot(L)} + M_{pot(R)}$ is the potentially mineralizable mass (g kg^{-1}) estimated using Equation (2). The value of $MF_{(cal\ 3)}$ corresponds to the annual mineralization fraction (365 days of degradation) of the organic material.

To evaluate the aerial biomass productivity of tifton 85 grass, the aerial portion of the plant was cut to 3 cm in relation to the soil surface to quantify the dry matter productivity 180 days after planting. The results were analyzed via analysis of variance and the means were compared using the Tukey test, adopting 5% significance.

RESULTS

The water content and temperature of the organic residue-soil mixture in the holes were between 14.0 and 20.0 dag kg^{-1} and 22–26 °C, respectively. From the time that the organic residue was incorporated into the soil (time zero) to after 100 days, the water content decreased to 4–8 dag kg^{-1} and a maximum temperature of 27 °C was recorded. This decrease in water content and increase in soil temperature resulted from a drought period between June and September 2016. The final measurement, taken at 215 days (first week of January 2017), indicated an increase in the water content to between 12.0 and 14.0 dag kg^{-1} and a decrease in temperature to 21–23 °C. Variations in the water content and temperature of the organic residue-soil mixture are among the main factors influencing the degradation rate of organic compounds dependent on the environmental conditions to which the residue was exposed (Paterson & Sim 2013).

Figure 3 shows curves adjusted to the accumulated mineralization data of the TOC_{min}, OOC_{min} and ON_{min}, respectively, according to the monitoring time after incorporating the sludge into the soil, under field conditions. The two-phase kinetic model, proposed by Inobushi *et al.* (1985), fit the data better than the model proposed by Stanford & Smith (1972) for the three treatments, at the minimum significance level of 5% for the coefficients.

With respect to the adjusted parameters for the single-phase model, values of the potentially mineralizable mass were between 0.2147 and 0.2246 dag kg^{-1} of TOC, 0.088 and 0.1381 dag kg^{-1} of OOC, and from 0.0174 to 0.0231 dag kg^{-1} of ON. Matos *et al.* (2017) observed values of 1.2609, 0.7752 and 0.4359 dag kg^{-1}, respectively, for potentially mineralizable TOC, OOC and ON after incorporating anaerobically digested sewage sludge at the rate of 50 g m^{-2} $year^{-1}$ of N during a 131 day monitoring period. Paula *et al.* (2013) found potentially mineralizable OOC and ON values of 6.7203 and 0.3711 dag kg^{-1}, respectively, in the incorporation of anaerobically digested sewage sludge at the application rate of 33 g m^{-2} $year^{-1}$ of N during a period of 360 days. The lower values of potentially mineralizable TOC, OOC and ON obtained in this work are directly associated with the greater biochemical stabilization of the organic residues accumulated in the VF-CW.

When analyzing the values of the two-phase equations for the adjusted curves, CWL 0–5 showed the highest mineralization potential of the most labile fraction of TOC, CWL 5–10 showed the highest OOC value and the ON values were similar among the top and bottom layers of the VF-CW, being lowest in the 5–10 cm layer.

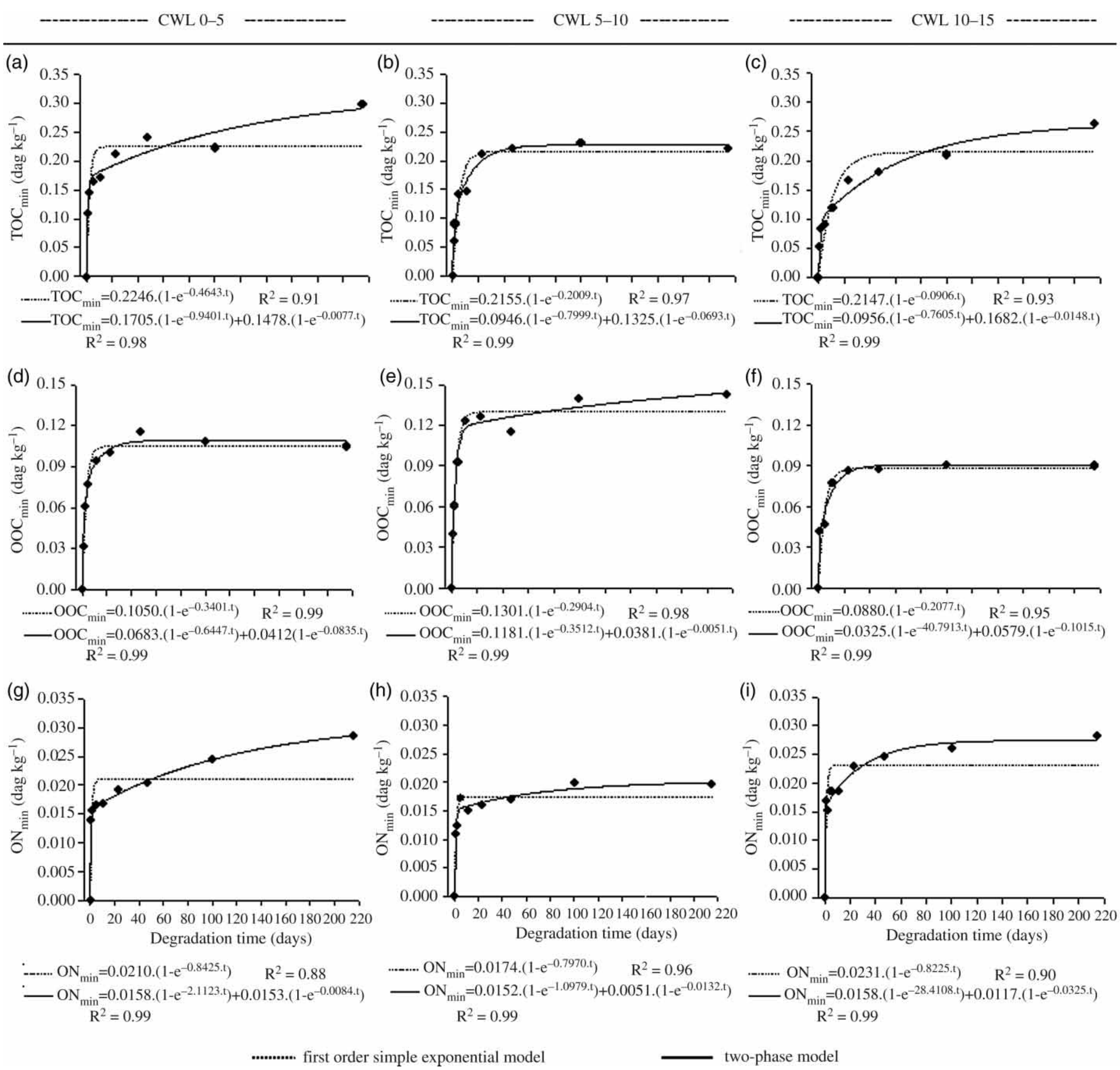

Figure 3 | Accumulated mineralized mass of total organic carbon (panels a, b, c), easily oxidizable organic carbon (panels d, e, f) and organic nitrogen (panels g, h, i) per unit mass of the organic residue-soil mixture and respective curves adjusted to the data obtained during the 215 day monitoring period after their incorporation into the soil under field conditions.

These results corroborate those obtained by Uggetti *et al.* (2009) and Matamoros *et al.* (2012), who also found greater stability of organic matter from organic residues accumulated in the lower layers of the VF-CW, i.e. those that remained in the system for a longer period.

In relation to the organic material mineralization coefficient for the single-phase equations, the values decreased from the shallow to deep organic waste collection point in the VF-CW, except for the ON_{min} at a depth of 10–15 cm (Figure 3(i)), which was greater than that obtained at the depth of 5–10 cm (Figure 3(h)). The high mineralization coefficients (k) obtained in the first days after incorporating the organic residue into the soil can be justified by the OOC/TOC ratio of the organic residues equal to 0.57 (Table 1). Matos *et al.* (2017) reported an OOC/TOC ratio of 0.31 in anaerobically digested sewage sludge incorporated into soil and this resulted in lower k coefficients (0.0359 d^{-1}), similar to those reported by Torri *et al.* (2003) when analyzing sewage sludge incorporated into typical acidic Argentine soils, who obtained a k value for OOC of 0.030–0.035 d^{-1}.

The mineralization coefficient of ON (k_N) obtained by Matos *et al.* (2017) for superficial mineralization (0.0367 d^{-1}) is smaller than the values reported by Moore *et al.* (2004) from swine wastewater which were 0.070 d^{-1} in the fall, 0.075 d^{-1} in the winter, 0.22 d^{-1} in the spring and 0.36 d^{-1} in the summer, however they were still smaller than those obtained in the present study.

When comparing the first phase of the adjusted equations, the average mineralization coefficients ($k(L)$) average values for the three layers of TOC, OOC and ON were equal to 61.8, 158.8 and 121.3 times higher than that obtained in the second phase ($k(R)$), respectively which indicates a high mineralization rate for organic material in the first 20 days, some stability for up to 100 days, followed by a small incremental phase to 215 days.

According to Andrade *et al.* (2013), sewage sludge organic matter consists predominantly of recalcitrant materials and is dependent on the intensity of the biological processes for its stabilization. However, the mineralization of organic carbon, nitrogen and phosphorus present in organic waste applied to the soil occurs more intensely in the first month, the period during which components of easier degradation are available (Dossa *et al.* 2008).

Table 2 shows the applied, mineralized and potentially mineralizable masses obtained in the adjustment of Equation (2) and recalculated for the time of 215 days of monitoring (min (cal)), in addition to estimates of the mineralized fractions of TOC, OOC and ON obtained when using Equations (3) and (4). Analyzing the results of the applied mass quantities, it was verified that in many situations the mineralized fraction was higher than that applied which indicates that the organic residue incorporated into the soil provided a priming effect, which stimulated the mineralization of native organic matter in the soil (Paula *et al.* 2013).

The mineralization fractions (MF) calculated in the experiment conducted under field conditions were greater than 92.0%, except for the CWL 10–15 sample, in which the MF was 86.1% for OOC, and when estimated for the time of 365 days the results were greater than 96.2%. The obtained MF values are close to those obtained in other studies (Paula *et al.* 2013; Pereira *et al.* 2015; Diniz *et al.* 2016; Matos *et al.* 2017) conducted under field and tropical climate conditions. In the literature (Roig *et al.* 2012), MF values for biosolids were reported after being incorporated into the soil at the incubation time of 130 days, in the range of 20–60% of total C added. Oba & Nguyen (1982) obtained MF values for ON of 55.8% after incorporating

Table 2 | Estimate of the TOC, OOC and ON mineralization fraction of the organic residues obtained from the VF-CW, obtained from the conceptual model and equations of the two-phase models adjusted to the data obtained in experiments conducted under field conditions

		$M_{(incorp)}$ g kg^{-1}	$M_{(min)\ obs}$	$M_{pot\ (L)} + M_{pot\ (R)}$	$M'_{(min)\ cal}$	$MF_{(cal\ 1)}$ %	$MF_{(cal\ 2)}$	$M'_{(min)\ cal}$ G kg^{-1}	$MF_{(cal\ 3)}$ %
Variables	**Organic residue**	**215 days**						**365 days**	
TOC	CWL 0–5	1.99	2.968	3.183	2.901	100	91.1	3.094	97.2
	CWL 5–10	2.11	2.211	2.271	2.271	100	100	2.271	100
	CWL 10–15	1.77	2.638	2.638	2.568	100	97.3	2.630	99.7
OOC	CWL 0–5	1.13	1.050	1.095	1.095	96.9	100	1.095	100
	CWL 5–10	1.16	1.425	1.562	1.437	100	92.0	1.503	96.2
	CWL 10–15	1.05	0.90	0.904	0.904	86.1	100	0.904	100
ON	CWL 0–5	0.15	0.286	0.311	0.286	100	91.9	0.304	97.7
	CWL 5–10	0.14	0.196	0.203	0.200	100	98.5	0.203	99.8
	CWL 10–15	0.14	0.283	0.275	0.275	100	99.9	0.275	99.9

$M_{(incorp)}$: organic residue mass incorporated into the soil; $M_{(min)\ obs}$: accumulated mineralized mass observed after 215 days of organic material degradation; $M_{pot\ (L)} + M_{pot\ (R)}$: potentially mineralizable mass of the most labile and recalcitrant fraction of the organic residue in the soil; $M'_{(min)\ cal}$: potentially mineralizable mass of the most labile and recalcitrant fraction of the organic residue in the soil, calculated at the time of monitoring using the two-phase model; MF: mineralization fraction calculated according to the expression: $MF_{(cal\ 1)} = M'_{(min)\ cal}/(M_{(incorp)}) * 100$; $MF_{(cal\ 2)} = M'_{(min)\ cal}/(M_{pot\ (L)} + M_{pot\ (R)}) * 100$; $MF_{(cal\ 3)}$ is the same as $MF_{(cal\ 2)}$ but for an estimate at 365 days; TOC, total organic carbon; OOC: easily oxidized organic carbon; ON, organic nitrogen.

and incubating unlimed sewage sludge for 30 days, in oxidic soil. Using sewage sludge processed in an extended aerobic sewage activation system with continuous flow, Giacomini *et al.* (2015) obtained 45.3% and approximately 60% for the MF of TOC and MF of ON, respectively, after 110 days of incubation in a sandy soil. This value of the MF for ON is at the upper limit of a wide range of mineralization indices (24–59%) determined in many different studies where aerobically treated sludge was used (Doublet *et al.* 2010). Pereira *et al.* (2015) credited the higher mineralization values to the residue incorporated into the soil, which provided better contact with the soil and permitted greater degradation when compared to spreading the residue on the soil surface. The authors obtained estimated values of k for OOC in residues incorporated into the soil and applied to the surface of 30 and 20 times greater than the values obtained in laboratory conditions. With regards to the k for ON, it was estimated that the incorporated residue and that applied to the surface were, respectively, about 3.2 and 1.6 times greater than the same application methods under laboratory conditions. These results underscore the fact that it is necessary to estimate the MF of organic residues in the field, since these fractions in the laboratory do not correspond to reality.

Figure 4 shows the results for dry matter productivity of the aerial part of tifton 85 grass for the application rate of 30 g m^{-2} of N incorporated into the soil at the significance level of 5% probability according to the Tukey test.

Comparatively, the productivity of dry matter from the aerial part of tifton 85 grass stimulated by fertilization with organic residues collected at different depths in the VF-CW was higher than that obtained in the control treatment

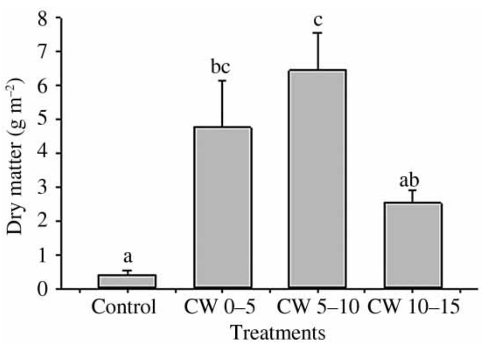

Figure 4 | Productivity of dry matter from the aerial portion of tifton 85 grass in unfertilized soil (control) and that fertilized with organic residues collected from different depths (CWL 0–5, CWL 5–10, CWL 10–15) of the VF-CW.

(soil without fertilization). The productivity obtained when incorporating CWL 5–10 was 15.8 times greater, indicating the fertilization potential of the organic residue. Higher yields obtained in the 0–5 and 5–10 cm layers are associated with the greater availability of nutrients for the plants, since these layers are composed of newer organic material and therefore have a lower degree of stabilization and leaching than the 10–15 cm layer.

The positive effect of fertilization with sewage sludge on agricultural crops has been highlighted in literature, i.e. application resulted in an increased content and supply of nutrients to the plants, and as a consequence, an increase in the dry matter production of the plant aerial part. Lemainski & Silva (2006) also reported that in a corn cultivation experiment, fertilization with sewage sludge was on average 21% more efficient than mineral fertilizer. In the present study there was an 11-fold increase in productivity of tifton 85 grass when fertilizing with VF-CW organic residue in relation to the zero dose of the control soil. In addition to improvements to the chemical conditions in the medium, it may be suspected that the improvement of physical properties may also have been a contributing factor to obtain greater productivity of the grass. It is believed that greater water retention was the factor that had the greatest influence on the results. According to Ferrer *et al.* (2011), the incorporation of sanitary sewage sludge improves the physical properties (structure and texture) of the soil, and can greatly influence plant growth.

The high productivity of tifton 85 grass fertilized with organic residues has been observed in several scientific articles. In a study by Matos *et al.* (2008), tifton 85 grass cultivated for four months showed high dry matter accumulation (1,500 g m^{-2}), and a relatively high capacity to remove nutrients (nitrogen, phosphorus and potassium) and sodium from dairy wastewater applied as fertigation to crops. Fia *et al.* (2011) studied planted HSSF-CWs for the treatment of swine wastewater, which resulted in average dry matter yields for the aerial parts of tifton 85 grass between 473 and 626 g m^{-2}, with cuttings at 90 and 150 days after planting. Baptestini *et al.* (2017) obtained yields of 820–980 g m^{-2} for the aerial portion of tifton 85 grass at three months of cultivation in HSSF-CWs used for the treatment of swine wastewater. Furthermore, when evaluating the performance of tifton 85 grass for the treatment of swine waste water, Amorim *et al.* (2015) obtained a dry matter productivity for the aerial portion of tifton 85 grass of 460 g m^{-2} $month^{-1}$.

Also based on the results obtained, the residence time of the sludge in the VF-CW for one year or more is sufficient for relative stabilization of the organic matter. The TVS/TS ratio decreased from 0.63 in the superficial layer (CWL 0–5) to 0.38 in the deepest layer (CWL 10–15), with no observed loss of fertilizer quality. This information may aid in decision making as an operational practice in these systems, and according to the degradability criteria this indicates that the organic residue removed can be disposed of in the soil of agricultural areas, readily adding available nutrients to the soil.

CONCLUSIONS

The storage/treatment of sludge in a VF-CW resulted in biochemically stabilized material. The degree of stability increased as the depth of collection in the referred system increased. Among the methods available for obtaining the value of the mineralization fraction, the ratio between the mineralized mass and the potentially mineralizable mass, estimated using the adjusted equations of the two-phase kinetic model, generated the most reliable results. The mineralized fractions of this organic material, considering the values of TOC, OOC and ON, estimated for 365 days under degradation in field conditions, were greater than 96%. The incorporation of these organic residues into the soil resulted in a considerable increase in tifton 85 grass productivity in relation to the treatment without fertilization. Based on results obtained for the mineralization fraction and the operational history of the VF-CW, the residence time of the septic tank sludge on the VF-CWs should be greater than one year, since in this period the material achieves sufficient stabilization but still maintains its value as an agricultural fertilizer.

ACKNOWLEDGEMENTS

The authors thank the 'Conselho Nacional de Desenvolvimento Científico e Tecnológico' (CNPq) and 'Coordenação de Aperfeiçoamento de Pessoal de Nível Superior' (CAPES) for financial support.

REFERENCES

Alvarenga, P., Mourinha, C., Farto, M., Santos, T., Palma, P., Sengo, J., Morais, M. C. & Cunha-Queda, C. 2015 Sewage sludge, compost and other representative organic wastes as agricultural soil amendments: benefits *versus* limiting factors. *Waste Manage.* **40** (3), 44–52.

Amorim, F., Fia, R., Pasqualin, P. P., Oliveira, L. F. C. & Silva, J. R. M. 2015 Capim-tifton 85 cultivado em sistema alagado construído com elevadas taxas de aplicação (Tifton grass in constructed wetlands with high loads). *Rev. Eng. Agric.* **23** (3), 241–250.

Andrade, C. A., Silva, L. F. M. & Coscione, A. R. 2013 Mineralização do carbono e do nitrogênio no solo após sucessivas aplicações de lodo de esgoto (Mineralization of carbon and nitrogen in soil after successive applications of sewage sludge). *Pesq. Agrop. Bras.* **48** (5), 536–544.

Andrade, C. F., von Sperling, M. & Manjate, E. S. 2017 Treatment of septic tank sludge in a vertical flow constructed wetland system. *Eng. Agríc.* **37** (4), 811–819.

Baptestini, G. C. F., Matos, A. T., Martinez, M. A., Borges, A. C. & Matos, M. P. 2017 Hydraulic conductivity variability in horizontal subsurface flow constructed wetlands. *Eng. Agríc.* **37** (2), 333–342.

Calderón-Vallejo, L. F., Andrade, C. F., Manjate, E. S., Madera-Parra, C. A. & von Sperling, M. 2015 Performance of a system with full- and pilot-scale sludge drying reed bed units treating septic tank sludge in Brazil. *Water Sci. Technol.* **71** (12), 1751–1759.

Diniz, I. C. C., Matos, A. T., Borges, A. C., Aquino, J. M. G. & Matos, M. P. 2016 Degradation of sewage sludge compost disposed on the soil. *Eng. Agríc.* **36** (5), 822–829.

Dossa, E. L., Khouma, M., Diedhiou, I., Sene, M., Kizito, F., Badiane, A. N., Samba, S. A. N. & Dick, R. P. 2008 Carbon, nitrogen and phosphorus mineralization potential of semiarid Sahelian soils amended with native shrub residues. *Geoderma* **148**, 251–260.

Doublet, J., Francou, C., Pétraud, J. P., Dignac, M. F., Poitrenaud, M. & Houot, S. 2010 Distribution of C and N mineralization of a sludge compost within particle-size fractions. *Bioresour. Technol.* **101** (4), 1254–1262.

Ferrer, A., Mochón, I., Oña, J. & Osorio, F. 2011 Evolution of the soil and vegetation cover on road embankments after the application of sewage sludge. *Water Air Soil Poll.* **214**, 231–240.

Fia, F. R. L., Matos, A. T., Fia, R., Lambert, T. F. & Matos, M. P. 2011 Remoção de nutrientes por *Typha latifolia* e *Cynodon* spp. cultivadas em sistemas alagados construídos (Nutrients removal by *Typha latifolia* and *Cynodon* spp. grown in constructed wetlands). *Rev. Ambiente-Água* **6** (1), 77–89.

Giacomini, S. J., Simon, V. L. G., Aita, C., Bastos, L. M., Weiler, D. A. & Redin, M. 2015 Carbon and nitrogen mineralization in soil combining sewage sludge and straw. *Rev. Bras. Ci. Solo.* **39**, 1428–1435.

Inobushi, K., Wada, H. & Takai, Y. 1985 Easily decomposable organic matter in paddy soil. VI. Kinetics of nitrogen mineralization in submerged soils. *Soil Sci. Plant Nutrition* **34**, 563–572.

Lemainski, J. & Silva, J. E. 2006 Avaliação agronômica e econômica da aplicação de biossólido na produção de soja (Agronomic and economic evaluation of biosolid application on soybean production). *Pesq. Agrop. Bras.* **41**, 1477–1484.

Matamoros, V., Nguyen, L. X., Arias, C. A., Nielsen, S., Laugen, M. M. & Brix, H. 2012 Musk fragrances, DEHP and heavy metals in a 20 years old sludge treatment reed bed system. *Water Res.* **46**, 3889–3896.

Matos, A. T. 2015 *Manual de Análise de Resíduos Sólidos E águas Residuárias (Manual Analysis of Solid Waste and Wastewater)*. UFV, Viçosa, Brasil.

Matos, A. T., Abrahão, S. S. & Pereira, O. G. 2008 Desempenho agronômico de capim tifton 85 (*Cynodon* spp.) cultivado em sistemas alagados construídos utilizados no tratamento de água residuária de laticínios (Agronomic performance of tifton 85 (*Cynodon* spp.) grass cultivated in constructed wetlands used in milk processing wastewater treatment). *Rev. Ambiente-Água* **3** (1), 43–53.

Matos, A. T., Diniz, I. C. C., Matos, M. P., Borges, A. C. & Pereira, A. A. 2017 Degradation rate of anaerobically digested sewage sludge in soil. *J. Water Sanit. Hyg. Dev.* **8** (1), 17–26.

Moore, D. A., Mikkelsen, R. L. & Israel, D. W. 2004 Nitrogen mineralization of anaerobic swine lagoon sludge as influenced by seasonal temperatures. *Comm. Soil Sci. Plant Anal.* **35** (7–8), 991–1005.

Oba, Y. & Nguyen, Q. 1982 Decomposition of sewage sludge in soil: III – nitrogen mineralization of ^{15}N-labeled sewage sludge in soils. *Soil Sci. Plant Nutr.* **28** (1), 119–130.

Parnaudeau, V., Nicolardot, B. & Pagès, J. 2004 Relevance of organic matter fractions as predictors of wastewater sludge mineralization in soil. *J. Environ. Qual.* **33**, 1885–1894.

Paterson, E. & Sim, A. 2013 Soil-specific response functions of organic matter mineralization to the availability of labile carbon. *Global Change Biol.* **19**, 1562–1571.

Paula, J. R., Matos, A. T., Matos, M. P., Pereira, M. S. & Andrade, C. A. 2013 Mineralização do carbono e nitrogênio de resíduos aplicados ao solo em campo (Carbon and nitrogen mineralization of wastes applied to soil under field conditions). *Rev. Bras. Ci. Solo* **37**, 1729–1741.

Pereira, M. S., Matos, A. T., Borges, A. C. & Nunes, M. F. 2015 Mineralização do resíduo da pupunheira em condições de campo e laboratório (Mineralization of peach palm waste under field and laboratory conditions). *Eng. Agríc.* **35** (5), 918–930.

Roig, N., Sierra, J., Marti, E., Nadal, M., Schuhahcer, M. & Domingo, J. L. 2012 Long-term amendment of Spanish soils with sewage sludge: effect on soil functioning. *Agric. Ecosystem Environ.* **158**, 41–48.

Stanford, G. & Smith, S. J. 1972 Nitrogen mineralization potential of soils. *Soil Sci. Soc. Am. Proc.* **36**, 465–472.

Stefanakis, A. I. & Tsihrintzis, V. A. 2012 Heavy metal fate in pilot-scale sludge drying reed beds under various design and operation conditions. *J. Hazard. Mater.* **213** (214), 393–405.

Suntti, C., Magri, M. E. & Philippi, L. S. 2011 Filtros plantados com macrófitas de fluxo vertical aplicados na mineralização e desaguamento de lodo de tanque séptico (Vertical flow constructed wetlands for septic sludge mineralization and dewatering). *Eng. Sanit. Amb.* **16** (1), 63–72.

Torri, S., Alvarez, R. & Lavado, R. 2003 Mineralization of carbon from sewage sludge in three soils of the argentine pampas. *Comm. Soil Sci. Plant Anal.* **34** (13–14), 2035–2043.

Uggetti, E., Llorens, E., Pedescoll, A., Ferrer, I., Castellnou, R. & García, J. 2009 Sludge dewatering and stabilization in drying reed beds: characterization of three full scale systems in Catalonia, Spain. *Bioresour Technol.* **100** (17), 3882–3890.

Uggetti, E., Ferrer, I., Nielsen, S., Arias, C., Brix, H. & Garcia, J. 2012 Characteristics of biosolids from sludge treatment wetlands for agricultural reuse. *Ecol. Eng.* **40**, 210–216.

First received 15 August 2018; accepted in revised form 28 February 2019. Available online 28 March 2019