

# Decomposition and nutrient release pattern of animal manures biodegraded by fly larvae in Acrisols

Adin Y. Bloukounon-Goubalan, Aliou Saïdou, Noël Obognon, Guillaume L. Amadji, Attanda M. Igué, Victor A. Clottey, and Marc Kenis

**Abstract:** This study aims to assess the decomposition of manure biodegraded by fly larvae and the nutrient mineralization rates to understand the efficiency of the biodegraded manures for further use as soil amendment. A litter bag experiment was carried out over 75 d in an Acrisol in Benin using poultry manure, pig manure, mixture of poultry and sheep manure, mixture of poultry and cow manure, and mixture of poultry and pig manure, biodegraded by *Musca domestica* larvae. Nutrients content in the manures during the different stages of decomposition was analyzed. The mono-component exponential model  $Y_t = Y_0 \times e^{-kt}$  best described the manure decomposition and nutrients mineralization. The manures decomposed fast in the soil, and their nutrients were released fast in the poultry manure, the mixture of poultry and pig manure, and the mixture of poultry and cow manure. Nutrient mineralization increased in the order of  $P < N < K$  or  $N < P < K$ . Biodegradation of animal manures by fly larvae produced high-quality organic fertilizer through fast N and P release. This could aid in reducing the quantities of these elements applied as mineral fertilizer by farmers for sustaining agricultural soil productivity.

**Key words:** organic manures, mineralization, fly larvae, soil fertility, modelling.

**Résumé :** L'étude devait évaluer la décomposition des fumiers biodégradés par les larves de mouche et la rapidité de la minéralisation des oligoéléments en vue de mieux comprendre l'utilité de tels amendements pour le sol. Les auteurs ont réalisé une expérience de 75 jours durant laquelle ils ont utilisé un sac à litière pour vérifier la décomposition d'un fumier fait de fiente de volaille, de déjections de porcs, d'un mélange de fiente de volaille et de déjections d'ovins, d'un mélange de fiente de volaille et de déjections de bovins ou d'un mélange de fiente de volaille et de déjections de porc sur un sol ferrallitique (Acrisol). Tous ces fumiers avaient été dégradés biologiquement par des larves de *Musca domestica*. Les auteurs ont dosé les oligoéléments dans le fumier aux diverses étapes de sa décomposition. Le modèle exponentiel à une composante  $Y_t = Y_0 \times e^{-kt}$  décrit le mieux la décomposition du fumier et la minéralisation des nutriments. Le fumier de fiente de volaille, celui de mélange de fiente de volaille et de déjections de porcs et celui de mélange de fiente de volaille et de déjections de bovins se décomposent et libèrent leurs éléments nutritifs rapidement dans le sol. La minéralisation des nutriments dans le sol augmente dans l'ordre  $P < N < K$  ou  $N < P < K$ . La biodégradation du fumier par les larves de mouche donne un engrais organique très fertilisant en raison de la rapidité avec laquelle le N et le P sont libérés. On pourrait s'en servir pour diminuer la quantité d'engrais minéraux que les agriculteurs emploient pour augmenter le rendement de leurs terres. [Traduit par la Rédaction]

**Mots-clés :** fumier biologique, minéralisation, larves de mouche, fertilité des sols, modélisation.

Received 28 June 2018. Accepted 26 November 2018.

**A.Y. Bloukounon-Goubalan, A. Saïdou, and N. Obognon.** Integrated Soil and Crops Management (ISCM) Research Unit, Laboratory of Soil Sciences, School of Crop Science, Faculty of Agronomic Sciences, University of Abomey-Calavi, P.O. Box 2819, RP Cotonou, Benin.

**G.L. Amadji.** Eco-Pedology Research Center, Laboratory of Soil Sciences, School of Crop Science, Faculty of Agronomic Sciences, University of Abomey-Calavi, P.O. Box 2819, RP Cotonou, Benin.

**A.M. Igué.** Laboratory of Soil Science Water and Environment (LSSEE), CRA Agonkanmey, National Institute of Agriculture Researches (INRAB), P.O. Box 884, RP Cotonou, Benin.

**V.A. Clottey.** CABI, CSIR Campus, No. 6 Agostino Neto Road, Airport Residential Area, P.O. Box CT 8630, Cantonments, Ghana.

**M. Kenis.** CABI, Rue des Grillons 1, 2800, Delémont, Switzerland.

**Corresponding author:** A.Y. Bloukounon-Goubalan (email: [adinbloukounon@gmail.com](mailto:adinbloukounon@gmail.com)).

Copyright remains with the author(s) or their institution(s). Permission for reuse (free in most cases) can be obtained from [RightsLink](https://www.copyright.com).

## Introduction

In sub-Saharan Africa, population-growth-driven land use intensification has contributed to soil fertility degradation (Tan et al. 2005). Consequently, nutrient depletion is widespread in many soils, and nutrient balances are negative for many cropping systems (Yusuf et al. 2009). In Benin, due to continuous cropping without external nutrient input, nutrient budgets are negative, resulting in soil fertility depletion, especially in the southern part of the country (Saïdou et al. 2003). The low organic matter content in these soils (Igue et al. 2013) and the exclusive use of inorganic fertilizer in cotton and maize cropping systems increase the risks of nitrogen (N) leaching and water pollution. The addition of organic materials to soil is the suitable solution to increase soil organic carbon (OC) storage (Powlson et al. 2012), enhance soil water-holding capacity (Pandey and Shukla 2006), decrease bulk density (Lynch et al. 2005), and improve soil fertility (Mader et al. 2002). Organic amendment to soils recycles nutrients and organic matter to support crop productivity and maintain soil fertility (Whalen et al. 2001). However, the choice of material as organic amendments will depend not only on the trade-offs in its various uses (Erenstein et al. 2015) but also on its availability and especially its quality.

Several technologies are currently used to improve organic wastes' quality. Composting converts the active organic portion in solid waste into a stabilized product, which can be used as a nutrient source for plant growth and (or) as a conditioner to improve soil properties (Huang et al. 2006). Vermicompost is the microbial composting of organic wastes through earthworm activity to form an organic fertilizer that contains high level of organic matter, OC, total and available N, phosphorus (P), potassium (K), and micronutrients, microbial and enzyme activities (Parthasarathi et al. 2008). But, the large amounts of bulking agents, such as sawdust, litter, and rice chaff, must be added for composting of amorphous materials like pig manure, sewage sludge, or poultry dung, which increases the cost of composting and dilutes the N, P, and K content in organic fertilizers (Zhang and Mastuto 2011).

The biodegradation of organic waste by fly larvae including *Hermetia illucens* and *Musca domestica* is an advanced technology that generates a stable bio-product (Zhang et al. 2014; Wang et al. 2016; Bloukounon-Goubalan et al. 2017). To appreciate the quality of the organic manures biodegraded by fly larvae, mineralization studies are necessary to be conducted in the same way as done for compost and vermicompost in the literature. In fact, the nutrient release dynamics and decomposition in the soil of manure biodegraded by fly larvae have not yet been studied in-depth especially on Acrisols. Knowing the kinetics of the mineralization process, one could relate the amount of nutrient released to plant nutrient requirements. It will also be

used as a tool to integrate current knowledge to quantify the amount of organic manure to be applied during fertilization or to predict organic matter dynamics in the soil to enhance crop production (Saïdou et al. 2016). It is known that easily decomposable material such as domestic waste, poultry manure, pig manure, and even human excreta are suitable for biodegradation by fly larvae (Diener et al. 2011; Bloukounon-Goubalan et al. 2017).

Many researches have demonstrated that the first order of mono-component model describes well the decomposition and nutrients mineralization of the easily decomposable organic materials (Nourbakhsh 2007; Bokossa et al. 2014; Saïdou et al. 2016). In this model, the logarithm of the average relative mineralization rate,  $k$ , or rate constant of a substrate considered as a whole was found to be linearly related to the logarithm of time,  $t$ , provided prevailing soil conditions remained unchanged (Yang and Janssen 2000).

This paper aims to assess the decomposition and nutrients mineralization rates of the animal manure biodegraded by fly larvae. Specifically, it aims at (i) assessing the suitable model of the decomposition and nutrients mineralization of animal manure biodegraded by the house fly, *M. domestica* larvae; (ii) assessing the kinetics of the decomposition process and nutrients release pattern of animal manure biodegraded by *M. domestica* larvae in an Acrisol.

## Material and Methods

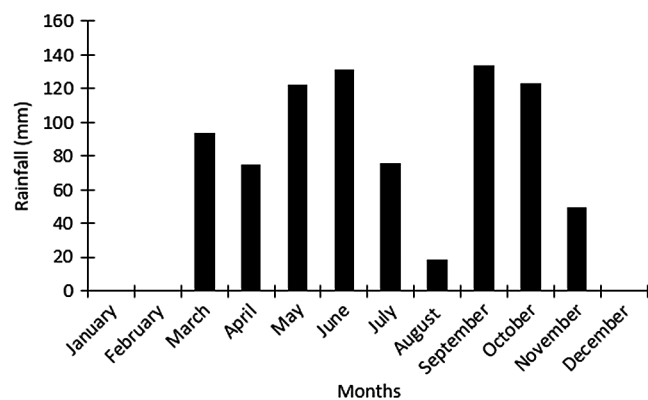
### Study areas

The trial was carried out in 2016 at the experimental site of the Faculty of Agronomic Sciences of the University of Abomey-Calavi located at Sékou (Allada municipality) in southern Benin. It is located around the longitude of 002°14'308 E, the latitude of 06°37'484 N, and at an altitude of 175 m a.s.l. The mean annual temperature was 28 °C, and the site received about 306 mm rainfall during the period of the experiment. Figure 1 presented the rainfall distribution during the year. The soil is classified as Acrisols (United States Department of Agriculture 1998) from the continental terminal. The pH (water) was 5.3. That soil is known to be poor in organic matter (Saïdou et al. 2003), and it require organic amendment for sustainable crop production.

### Biodegradation of the substrates by fly larvae

Five organic manures or mixture of organic manures were biodegraded by larvae of *M. domestica*. Organic substrates were pig manure, poultry manure, mixture of poultry and cow manure, mixture of poultry and sheep manure, and then mixture of poultry and pig manure. The ratio of the manure mixtures was 1:1. In fact, all of these substrates underwent 12 d of biodegradation, which subdivided into three stages due to the growth cycle of the flies. Each stage lasted for 4 d at the

**Fig. 1.** Rainfall distribution in the study areas in Sékou, Allada, 2016.



end of which the fly larvae were harvested. After harvesting the larvae, 1 kg of new fresh organic manure or mixture of organic manure was added to the remaining organic manure for the second stage of biodegradation. The same was applied to the remaining manure for the third stage of biodegradation. The biodegradation process occurred in the containers by exposing 3 kg of each organic manure at 65%–75% moisture content to natural fly oviposition. Ten hours after natural oviposition, the containers were covered with a net to obtain larva cohort of the same generation.

#### Experimental design and decomposition process of biodegraded substrates in soil

After the biodegradation, the manures collected were dried at 65 °C. About 200 g of the dry manures were placed into 20 cm × 20 cm nylon meshed litter bag (1 mm mesh size) for the decomposition process in the soil. The experimental design was a randomized complete block with eight replications. Five bags of each manure were constituted to process samples at 15, 30, 45, 60, and 75 d of decomposition in the soil. Thus, a total of 200 nylon mesh bags with manures were buried in the soil at 15 cm depth and at a spacing of 2 m × 2 m. During the removal of each bag, the remaining manures were oven-dried at 65 °C and weighed to determine the remaining mass. Samples of each initial manure and the remaining manure were analyzed for their nutrients content.

#### Chemical analysis of the manures

The samples were analyzed at the International Crops Research Institute for the Semi-Arid Tropics laboratory at Niamey, Niger for OC, total N, total P, total K, total calcium (Ca), and total magnesium (Mg). Organic carbon was determined according to Walkley and Black wet oxidation method. Concentrated H<sub>2</sub>SO<sub>4</sub> was added to a mixture of sample and 1 mol L<sup>-1</sup> K<sub>2</sub>Cr<sub>2</sub>O<sub>7</sub> solution leading to oxidation of organic matter. The residual dichromate was titrated against iron sulfate. Furthermore, after digestion in a mixture of concentrated sulfuric acid

(H<sub>2</sub>SO<sub>4</sub>), salicylic acid (C<sub>7</sub>H<sub>6</sub>O<sub>3</sub>), hydrogen peroxide (H<sub>2</sub>O<sub>2</sub>), and selenium as a catalyst by heating to about 330 °C for 3 h, total P was measured by spectrophotometry in ammonium molybdate solution with ascorbic acid at a wavelength of 660 nm. Determination of total N was carried out from the same digest by spectrophotometry with auto-Analyzer using Bertholet reaction. From the same digest, K, Ca, and Mg were determined by atomic absorption spectrophotometry using Perkin–Elmer model Analyst 400.

#### Data analysis

Statistical differences in the organic manures and between decomposition period were performed using generalized linear model function for the analysis of variance using the R version 3.0.2 software, and Student–Newman–Keuls test at  $\alpha = 0.05$  was used for mean separation. The first-order equation of mono-component model with a constant relative mineralization rate proposed by Henin and Dupuis (1945) was fitted using eq. 1. Adjusted R<sup>2</sup> was used for judging the fit between models and observations using the most general definition (Yang 1996; Spiess and Neumeyer 2010). The half-life values of the manure decomposition and mineralization were calculated from eq. 2 suggested by Olson (1963).

$$(1) \quad Y_t = Y_0 \times e^{-kt}$$

$$(2) \quad t_{1/2} = 0.693/k$$

where  $Y_t$  and  $Y_0$  are the percentage of weight or nutrient of substrate, respectively, at time  $t$  and 0;  $k$  is the relative mineralization rate. To test the models described above, the significance of the  $k$  and  $Y_0$  was checked.  $t_{1/2}$  is the half-life of the manure.

## Results

#### Chemical characteristics of the organic manures

The chemical characteristics of the manures before and after biodegradation by *M. domestica* larvae are presented in Tables 1 and 2, respectively. After the biodegradation by *M. domestica* larvae, the mixture of poultry and pig manure and the poultry manure alone had the highest OC content ( $340.2 \pm 0.6$  and  $298.4 \pm 0.5$  g kg<sup>-1</sup>, respectively). Organic carbon content in the pig manure and in the mixture of poultry and sheep manure was similar ( $p > 0.05$ ) and lower than that in the poultry manure. The mixture of poultry and cow manure had the lowest OC content. Nitrogen content in the mixture of poultry and pig manure and in the poultry manure was significantly similar ( $p > 0.05$ ) but higher than that in the other manures (Table 2). Total P in the biodegraded manures ranged between  $10.3 \pm 0.0$  and  $25.3 \pm 0.0$  g kg<sup>-1</sup>. The poultry manure had the highest total P content followed by the mixture of poultry and pig manure at the end of the biodegradation process. The biodegraded poultry manure significantly had the highest K and Ca concentration, whereas the mixture of poultry and sheep had

**Table 1.** Initial characteristics (mean  $\pm$  standard error) of the substrates subjected to *Musca domestica* larvae biodegradation.

Substrate	Organic carbon (g kg <sup>-1</sup> )	Total nitrogen (g kg <sup>-1</sup> )
Pig manure	295.5 $\pm$ 0.5c	22.1 $\pm$ 0.5a
Poultry manure	375.6 $\pm$ 0.8a	22.3 $\pm$ 0.1a
Mixture of poultry and sheep manure	247.5 $\pm$ 0.5e	18.2 $\pm$ 0.3c
Mixture of poultry and cow manure	274.5 $\pm$ 0.5d	15.0 $\pm$ 0.1d
Mixture of poultry and pig manure	348.4 $\pm$ 1.2b	19.8 $\pm$ 0.4b

**Note:** Means with the same lowercase letter within a column are significantly ( $p > 0.05$ ) similar according to Student–Newman–Keuls test.

**Table 2.** Nutrient content (mean  $\pm$  standard error) in manure biodegraded and used in mineralization trial.

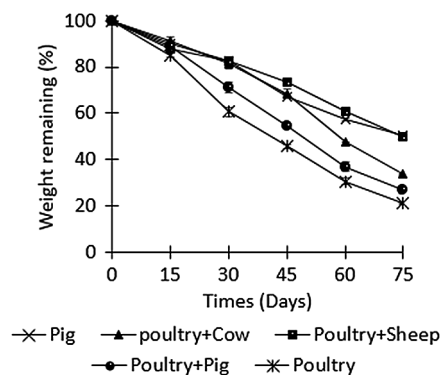
Manure biodegraded by fly larvae	Organic carbon (g kg <sup>-1</sup> )	Total nitrogen (g kg <sup>-1</sup> )	Total phosphorus (g kg <sup>-1</sup> )	Total potassium (g kg <sup>-1</sup> )	Total calcium (g kg <sup>-1</sup> )	Total magnesium (g kg <sup>-1</sup> )
Pig manure	205.7 $\pm$ 0.9c	16.9 $\pm$ 0.4b	10.3 $\pm$ 0.0d	6.0 $\pm$ 0.4d	0.033 $\pm$ 0.001e	0.067 $\pm$ 0.002d
Poultry manure	298.4 $\pm$ 0.5b	18.5 $\pm$ 0.3a	25.3 $\pm$ 0.0a	22.6 $\pm$ 0.6a	0.316 $\pm$ 0.003a	0.084 $\pm$ 0.002c
Mixture of poultry and sheep manure	204.6 $\pm$ 0.4c	10.6 $\pm$ 0.3c	13.7 $\pm$ 0.0c	11.5 $\pm$ 0.3b	0.228 $\pm$ 0.005c	0.583 $\pm$ 0.008a
Mixture of poultry and cow manure	152.2 $\pm$ 1.7d	8.8 $\pm$ 0.3d	10.7 $\pm$ 0.3d	2.5 $\pm$ 0.4e	0.251 $\pm$ 0.004b	0.042 $\pm$ 0.001e
Mixture of poultry and pig manure	340.2 $\pm$ 0.6a	18.7 $\pm$ 0.2a	18.7 $\pm$ 0.2b	9.7 $\pm$ 0.2c	0.077 $\pm$ 0.007d	0.133 $\pm$ 0.017b

**Note:** Means with the same lowercase letter within a column are significantly ( $p > 0.05$ ) similar according to Student–Newman–Keuls test.

the highest Mg concentration. The lowest Ca and Mg contents were, respectively, recorded in the pig manure and the mixture of poultry and cow manure at the end of the biodegradation process.

#### Decomposition pattern of manures in the soil

The trends of the manure weights remaining in the bags (Fig. 2) were significantly ( $p < 0.05$ ) different during the decomposition periods in the soil and also between the different types of manure. The weight of the poultry manure, mixture of poultry and the pig manure, and mixture of poultry and cow manure decreased faster than that of the pig manure and the mixture of poultry and sheep manure. After 15 d in the soil, the weight loss in the manures was significantly similar ( $p > 0.05$ ) according to the Student–Newman–Keuls test. But after 30–45 d in the soil, the weight loss in the poultry manure was significantly ( $p < 0.05$ ) different and twice higher than those of the pig manure, the mixture of poultry and sheep manure, and the mixture of poultry and cow manure. The weight loss in the pig manure and in the mixture of poultry and sheep manure was significantly similar ( $p > 0.05$ ) throughout the experiment and averaged at 50% of the initial mass after 75 d in the soil. Furthermore, after 75 d in the soil, the weight loss in the poultry manure, the mixture of poultry and pig manure, the mixture of poultry and cow manure was 79%, 73%, and 66%, respectively (Fig. 2).

**Fig. 2.** Decomposition pattern of animal manure substrates previously biodegraded by the fly larvae. Pig, pig manure; Poultry + Cow, mixture of poultry and cow manure; Poultry + Sheep, mixture of poultry and sheep manure; Poultry + Pig, mixture of poultry and pig manure; Poultry, poultry manure.

#### Kinetics of the decomposition and mineralization process of the manures in the soil

The first-order function of mono-component of manures decomposition and their nutrients mineralization trends in the soil are presented in Table 3. The model indicated that weight and nutrients remaining in each manure were a function of the initial nutrient content, the relative decomposition or mineralization rate, and the time. The adjusted  $R^2$  value varied between

**Table 3.** Exponential functions describing remaining mass and nutrients after decomposition of manures previously decomposed by fly larvae.

Type of manure	Parameter	Fitted model	Adjusted R <sup>2</sup>	Half-life period $t_{0.5}$ in fortnight
Pig manure	Mass remaining	$Y_t = 102.41e^{-0.137t}$	0.98	5.06***
	C	$Y_t = 110.68e^{-0.077t}$	0.95	9.00**
	N	$Y_t = 99.84e^{-0.101t}$	0.96	6.86***
	P	$Y_t = 99.25e^{-0.19t}$	0.97	3.65***
	K	$Y_t = 108.22e^{-0.286t}$	0.88	2.42**
	Ca	$Y_t = 106.39e^{-0.116t}$	0.96	5.97**
	Mg	$Y_t = 98.42e^{-0.249t}$	0.95	2.78***
Poultry manure	Mass remaining	$Y_t = 104.52e^{-0.285t}$	0.92	2.43***
	C	$Y_t = 100.57e^{-0.331t}$	0.95	2.09**
	N	$Y_t = 101.25e^{-0.303t}$	0.96	2.29***
	P	$Y_t = 102.53e^{-0.112t}$	0.96	6.19***
	K	$Y_t = 105.71e^{-0.437t}$	0.92	1.59**
	Ca	$Y_t = 105.09e^{-0.121t}$	0.96	5.73**
	Mg	$Y_t = 105.47e^{-0.269t}$	0.95	2.58**
Mixture of poultry and sheep manure	Mass remaining	$Y_t = 101.42e^{-0.125t}$	0.91	5.54***
	C	$Y_t = 104.80e^{-0.106t}$	0.92	6.54**
	N	$Y_t = 101.28e^{-0.037t}$	0.97	18.73***
	P	$Y_t = 99.57e^{-0.074t}$	0.97	9.36***
	K	$Y_t = 107.36e^{-0.289t}$	0.91	2.40**
	Ca	$Y_t = 99.31e^{-0.079t}$	0.96	8.77***
	Mg	$Y_t = 100.21e^{-0.149t}$	0.97	4.65***
Mixture of poultry and cow manure	Mass remaining	$Y_t = 106.25e^{-0.183t}$	0.91	3.79**
	C	$Y_t = 98.03e^{-0.105t}$	0.93	6.60**
	N	$Y_t = 90.38e^{-0.249t}$	0.84	2.78**
	P	$Y_t = 95.75e^{-0.101t}$	0.93	6.86**
	K	$Y_t = 102.36e^{-0.327t}$	0.98	2.12***
	Ca	$Y_t = 99.01e^{-0.054t}$	0.84	12.83*
	Mg	$Y_t = 105.30e^{-0.32t}$	0.93	2.17**
Mixture of poultry and pig manure	Mass remaining	$Y_t = 105.61e^{-0.237t}$	0.96	2.92***
	C	$Y_t = 99.44e^{-0.226t}$	0.99	3.07***
	N	$Y_t = 92.50e^{-0.269t}$	0.86	2.58**
	P	$Y_t = 100.16e^{-0.209t}$	0.95	3.32***
	K	$Y_t = 106.36e^{-0.272t}$	0.91	2.55**
	Ca	$Y_t = 104.07e^{-0.149t}$	0.86	4.65**
	Mg	$Y_t = 96.94e^{-0.137t}$	0.96	5.06***

**Note:**  $Y_t$  is mass fraction of the remaining manure or nutrient in a manure at a specific time ( $t$  in fortnight). \*\*\*,  $p < 0.001$ ; \*\*,  $p < 0.01$ ; \*,  $p < 0.05$ .

0.84 and 0.99. The decomposition rate of the manures varied widely and ranged between 12% and 28% fortnight<sup>-1</sup>. It increased in the following order: mixture of poultry and sheep manure < pig manure < mixture of poultry and cow manure < mixture of poultry and pig manure < poultry manure. The half-lives of the manures were 36, 44, 57, 76, and 83 d for the poultry manure, mixture of poultry and pig manure, mixture of poultry and cow manure, pig manure, and mixture of poultry and sheep manure, respectively.

The OC mineralization rate was the highest in the poultry manure ( $k = 0.022 \text{ d}^{-1}$ ) and the lowest in the pig manure ( $k = 0.0051 \text{ d}^{-1}$ ). It was three times higher in the poultry manure than that recorded in the mixture of poultry and sheep manure and mixture of poultry and

cow manure and then four times higher than that recorded in the pig manure. The half-lives of the manures' OC were 135, 99, 98, 46, and 31 d in the pig manure, the mixture of poultry and cow manure, the mixture of poultry and sheep manure, the mixture of poultry and pig manure, and then the poultry manure, respectively. Organic nitrogen mineralized faster in the poultry manure ( $k = 0.02 \text{ d}^{-1}$ ) than in the mixture of poultry and pig manure ( $k = 0.018 \text{ d}^{-1}$ ) and in the mixture of poultry and cow manure ( $k = 0.017 \text{ d}^{-1}$ ). The pig manure and the mixture of poultry and sheep manure recorded the lowest N mineralization rate, respectively,  $k = 0.0067$  and  $k = 0.0027 \text{ d}^{-1}$ . The half-lives of the organic N were 281, 103, 42, 39, and 34 d in the mixture of poultry and sheep manure, the pig manure, the mixture of

poultry and cow manure, the mixture of poultry and pig manure, and then the poultry manure, respectively. Moreover, the highest P mineralization rate recorded in the mixture of poultry and pig manure and in the pig manure was  $k = 0.014$  and  $k = 0.0127 \text{ d}^{-1}$ , respectively, whereas P mineralization rate was the lowest in the mixture of poultry and sheep manure ( $k = 0.0047 \text{ d}^{-1}$ ) than that of the mixture of poultry and cow ( $k = 0.0067 \text{ d}^{-1}$ ), and the poultry ( $k = 0.0073 \text{ d}^{-1}$ ). The half-lives of P were 140, 103, 93, 55, and 50 d, respectively, in the mixture of poultry and sheep manure, the mixture of poultry and cow manure, the poultry manure, the pig manure, and the mixture of poultry and pig manure. Furthermore, K mineralization rate in the different manure ranged from 1.9% to 2.9%  $\text{d}^{-1}$ , and the half-life of the manures' organic K varied between 24 and 38 d. The highest Ca mineralization rate ( $k = 0.0099 \text{ d}^{-1}$ ) was recorded in the mixture of poultry and pig manure. It was almost similar in the pig manure ( $k = 0.0077 \text{ d}^{-1}$ ) and the poultry manure ( $k = 0.0081 \text{ d}^{-1}$ ). Magnesium mineralization was faster in the mixture of poultry and cow manure ( $k = 0.022 \text{ d}^{-1}$ ) than that recorded in the poultry manure, the pig substrate (on average  $k = 0.017 \text{ d}^{-1}$ ), the mixture of poultry and sheep manure, and the mixture of poultry and pig manure (on average  $k = 0.0099 \text{ d}^{-1}$ ). In general, nutrient mineralization increased in the order of  $\text{N} < \text{P} < \text{K}$  in the pig manure and that of the mixture of poultry and sheep and then in the order of  $\text{P} < \text{N} < \text{K}$  in the other manures.

#### Changes in the manures' nutrient content during mineralization in the soil

The total amount of nutrients in each of manure decreased significantly ( $p < 0.05$ ) during the mineralization process in the soil (Fig. 3). The fractions of OC mineralized after 30 d of decomposition were significantly different ( $p < 0.05$ ) according to manures and were 60%, 39%, 21%, 8%, and 6% in the poultry manure, the mixture of poultry and pig manure, the mixture of poultry and cow manure, the mixture of poultry and sheep manure, and the pig manure, respectively. The poultry manure and that of the mixture of poultry and pig manure continued to lose an important fraction of OC throughout the experiment and mineralized 77% and 66% of the initial content after 75 d. But, the fractions of OC mineralized in the pig manure, the mixture of poultry and sheep manure, and the mixture of poultry and cow manure were 10%, 39%, and 41% of the initial content, respectively. The amount of nutrients mineralized was significantly different ( $p < 0.05$ ) during the decomposition period in each manure and then between manures ( $p < 0.05$ ) throughout the experiment (Fig. 3). Organic nitrogen was more mineralized in the poultry manure (81%), the mixture of poultry and pig manure (67%), and the mixture of poultry and cow manure (67%) than the remaining manures. Most of the N mineralized (53%) in the manures occurred before 30 d, whereas during the

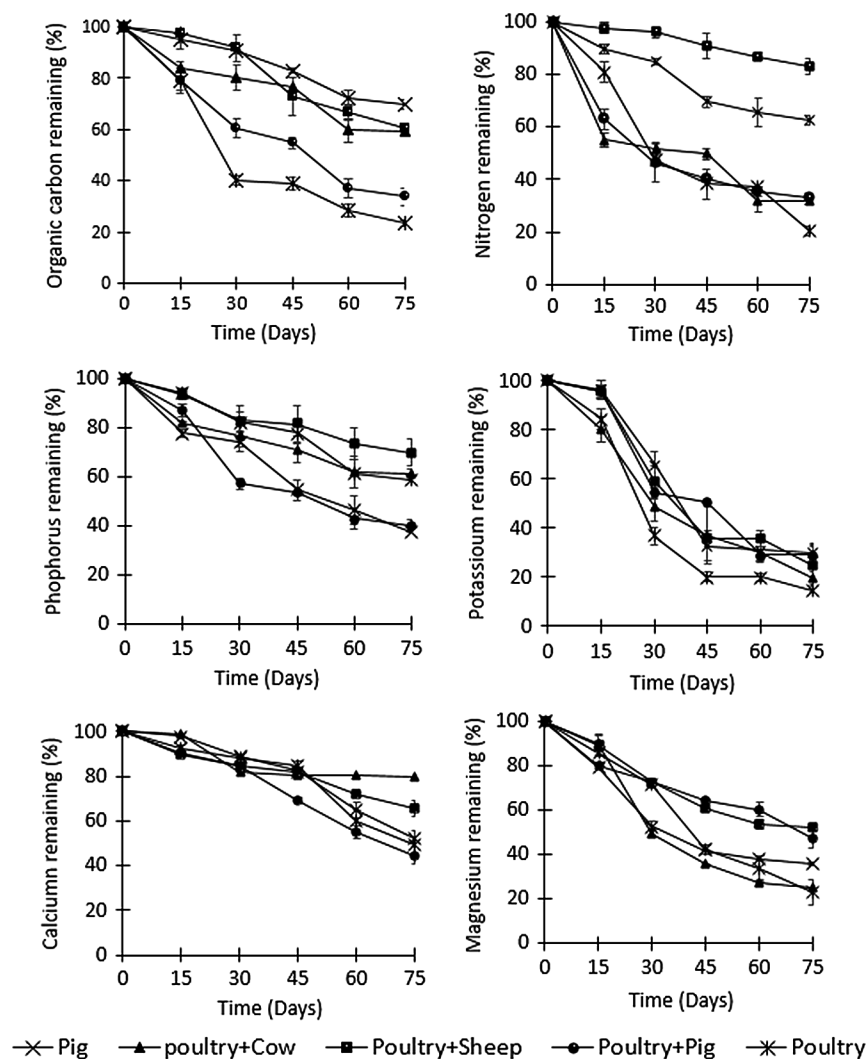
experiment, on average 17% and 38% of the OC were mineralized in the mixture of poultry and sheep manure and the pig manure, respectively. The highest amount of P released was recorded in the mixture of poultry and pig manure, and the pig manure (60%) and the lowest in that of the mixture of poultry and sheep (30%) manure. Total K was released continuously and similarly in the manures. At the end of the 75 d in the soil, from 71% to 86% of the K were released. Calcium released less than the other nutrients. The difference in the Ca released occurred mainly after 45 d till the end of the experiment with the lowest released in the mixture of poultry and pig manure and the highest released in the mixture of poultry and cow manure. Magnesium released significantly more ( $p < 0.05$ ) in the poultry manure and the mixture of poultry and cow manure than the others manures.

## Discussion

### Suitability of the first order of mono-component model to predict decomposition and mineralization of the substrates biodegraded by fly larvae

There is no study on the decomposition and mineralization in soil of the animal manure decomposed in advance by fly larvae. But, several researchers have fitted mineralization of organic matter with low-recalcitrant components, such as pig manure (Bokossa et al. 2014; Saidou et al. 2016), vermicomposted cow manure (Nourbakhsh 2007), composted manure (N'Dayegamiye et al. 1997), and certain leaves litter (Matus and Rodriguez 1994; Kayuki and Wortmann 2001) by using the first order of mono-component. In general, the multi-component models describe well the organic matter partitioned into several components according to their resistance to mineralization (Yang 1996). That model considers the existence of two or more fractions occurring in the process, a more-stable (lignin and polyphenol compounds) and a less-stable form (protein and soluble components). They were used to describe the C and N mineralization of maize residues (Lynch et al. 2016) and *Eucalyptus marginata* leaf litter (Qiu et al. 2012). The suitability of the first order of mono-component model to describe mineralization and decomposition of the substrates biodegraded by fly larvae is due to their high content in decomposable compounds. In fact, the biodegradation of initial substrate by fly larvae resulted in the reduction of C as carbon dioxide form, N as  $\text{NH}_4\text{-N}$  and  $\text{NO}_3\text{-N}$ , and substrate weight reduction (Zhu et al. 2012; Zhu et al. 2015; Wang et al. 2016; Bloukounon-Goubalan et al. 2017). Nourbakhsh (2007) reported similar results with vermicomposted cow manure. Thus, the current substrates biodegraded by fly larvae cannot be partitioned into several components according to their resistance to mineralization because their resistant fraction can be negligible. In general, recalcitrant compounds degrade after 5 yr in the fields (Hobbie 2000; Osono et al. 2008). The experimental period of 75 d was

**Fig. 3.** Nutrient's content changes in the manures during the mineralization in soil. Pig, pig manure; Poultry + Cow, mixture of poultry and cow manure; Poultry + Sheep, mixture of poultry and sheep manure; Poultry + Pig, mixture of poultry and pig manure; Poultry, poultry manure.



very short for observing the manures' behavior in the long term. The half-lives of most of the fractions of manure biodegraded by fly larvae did not exceed 100 d and indicated that the manures used were easily decomposable products.

#### Decomposition of substrates biodegraded by fly larvae

Poultry manure and the mixture of poultry and pig manure, which recorded the highest N contents were rapidly decomposed in the soil. This result point out the influence of N in the decomposition of organic material and confirmed that manures with high N content decomposes more rapidly than that with low N content. Our results corroborate the finding of Joffre and Agren (2001) who showed that different N concentrations of a given manures type (high or low C:N ratio) strongly affect the rate of respiration and net N mineralization, especially in the early stages of the

decomposition. The lowest decomposition rate of mixture of poultry and sheep substrates was probably due to the accumulation of recalcitrant components such as lignin and tannins because the sheep were feeding on fodder. Furthermore, Singh et al. (2006) reported that the application of a mixture of high and low C:N ratio in the manure can modulate the amount of N released, which can help minimize N loss from ecosystems. This explains the slow decomposition of the mixture of poultry and sheep manure as observed in this study. The lowest decomposition rate of the pig manure despite its C:N ratio of 12 indicated that C:N ratio was not a good indicator for appreciating the decomposition in the soil of manures biodegraded by fly larvae. In addition, the pig manure could provide higher stable organic matter as well as humus C than the others. This result confirms a previous finding, which showed that the biodegradation of pig manure by fly larvae induced more maturity to

the substrate than the other substrates (Bloukounon-Goubalan et al. 2017). This also justifies why most of the previous fly larvae biodegradation studies occurred on pig manure (Zhang et al. 2012; Zhu et al. 2015; Wang et al. 2016). The decomposition rate of the poultry manure was  $0.019 \text{ d}^{-1}$ , which was lower than that found by Khalil et al. (2005) with common poultry manure ( $0.025 \text{ d}^{-1}$ ) not decomposed by larvae. In addition, the decomposition rate of the pig manure was  $0.0013 \text{ d}^{-1}$  and was lower than that found by Saïdou et al. (2016) with the common pig manure ( $0.069 \text{ d}^{-1}$ ) not decomposed by fly larvae. These results prove that the biodegradation process by fly larvae improves the stability of the manure. Moreover, the decomposition of organic manures in soil depends mostly on soil nature, temperature, and precipitation (Eghball 2000; Keller et al. 2004). A high moisture content decreases rates of organic material decomposition, due to low oxygen supplies, whereas low soil moisture decreases microbial activity by reducing diffusion of soluble substrates, microbial mobility, and intracellular water potential (Schjønning et al. 2003). Thus, the absence of precipitation during the first fortnight could explain the low decomposition of the manures during that period.

#### Implications of nutrients mineralization of substrates biodegraded by fly larvae

The fraction of OC mineralized in the poultry manure was more than 75% at the rate of  $0.022 \text{ d}^{-1}$ . That value corroborates with those of Khalil et al. (2005) and Flavel and Murphy (2006) on poultry manure not decomposed by fly larvae. This result proves that the OC in the poultry manure was not resistant to the soil microbial degradation. According to Bernal et al. (2009), any compost in which more than 30% of OC is mineralized after 70 d is immature. Based on that, only the pig manure and to a lesser extent that of the mixture of poultry and sheep, and the mixture of poultry and cow manure reached the maturity through the biodegradation process by *M. domestica* larvae. The fraction of OC mineralized in the pig manure was closer to that recorded in some compost-based animal manure (De Neve et al. 2003). This finding proved that the pig manure biodegraded by fly larvae was an excellent bio-product. The N mineralization rates of the manures biodegraded by *M. domestica* larvae proved that they can provide the N requirement for vegetable crops during the growth and development stage. In addition, the rapid N mineralization rate observed in the manures showed that their organic N was easily decomposable. As a matter of fact, it was demonstrated that high weight loss and OC reduction in the manures during the biodegradation by fly larvae pointed to the decomposition of the macroproteins molecule leading to available inorganic N forms in the soil (Bloukounon-Goubalan et al. 2017). This is an interesting result since fast N releases if well managed could reduce N input as mineral fertilizer by farmers. Also, in

southern Benin as in most of the agricultural areas in sub-Saharan Africa, N is the most limiting nutrient (Saïdou et al. 2017) and the most important nutrient for vegetables and cereal crops. For example, incorporation of poultry manure biodegraded by *M. domestica* larvae in an Acrisol can provide 79% of its N content equivalent to  $15 \text{ g N kg}^{-1}$  of manure applied. Thus, in the short term, incorporation of these manures will provide the energy and N for microbial activity, and it will be the source of nutrients for the crops. Moreover, the rapid mineralization of P in pig manure showed that most of the P in the manure was in the inorganic form, which increased its availability in the soil after application (Eghball et al. 2002). Pitta et al. (2012) reported that P availability is beneficial to soil and crops because P improves soil microbial activity significantly. In addition, P is less available in the exchangeable form in the soil and is the most expensive nutrient. This is also an interesting result because P being the most expensive nutrient and is also less available in the soil, the pig manure and the mixture of poultry and sheep manure biodegraded by fly larvae can reduce the quantity of mineral fertilizer to be used as well as the cost of production leading to an increase in farmers' income. Furthermore, K is very mobile and prone to leaching in tropical soils (Bayala et al. 2005). At the 75 d of decomposition, 70%–85% of K were released in all manures. This result backs up those of Tian et al. (1992), Saïdou et al. (2016), and Kayuki and Wortmann (2001). This finding is important for farmers for the development of good practices such as the fractionation of manures for better K management. In general, nutrients mineralization increased in the order of  $\text{N} < \text{P} < \text{K}$  in the pig manure and that of the mixture of poultry and sheep and then in the order of  $\text{P} < \text{N} < \text{K}$  in the other manures. Thus, organic P was mineralized at a slower rate than organic N in the more stable manure.

#### Conclusion

The first-order mono-component equation model with a relative mineralization rate  $Y_t = Y_0 \times e^{-kt}$  describes well the decomposition and nutrients mineralization processes. Manures biodegraded by *M. domestica* larvae decomposed rapidly in the soil with a half-life of <1 yr. Nutrients especially N and K released slowly in the pig manure and in the mixture of poultry and sheep manure than the other manures. Biodegradation process by *M. domestica* larvae improved the maturity and stability of the manure. Regarding the results of nutrient mineralization kinetics, pig manure can provide plant N, P, and K requirement within a growing season.

#### Acknowledgements

The present study was carried out in the framework of the project, IFWA — sustainable use of insects to improve livestock production and food security in smallholder farms in West Africa, funded by the Swiss Agency for Development and Cooperation and the Swiss

National Science Foundation, in the framework of the Swiss Programme for Research on Global Issues for Development (R4D). Marc Kenis was partly funded through the CABI Development Fund (supported by contributions from the Australian Centre for International Agricultural Research, the UK's Department for International Development, and others).

## References

- Bayala, J., Mando, A., Teklehaimanot, Z., and Ouedraogo, S.J. 2005. Nutrient release from decomposing leaf mulches of karite (*Vitellaria paradoxa*) and nere (*Parkia biglobosa*) under semi-arid conditions in Burkina Faso, West Africa. *Soil Biol. Biochem.* **37**: 533–539. doi:10.1016/j.soilbio.2004.08.015.
- Bernal, M.P., Albuquerque, J.A., and Moral, R. 2009. Composting of animal manures and chemical criteria for compost maturity assessment. A review. *Bioresour. Technol.* **100**: 5444–5453. doi:10.1016/j.biortech.2008.11.027. PMID:19119002.
- Bloukounon-Goubalan, A.Y., Saïdou, A., Togbé, E., Chabi, F., Babatounde, S., Chrysostome, C.A.A.M., Kenis, M., and Mensah, G.A. 2017. Physical and chemical properties of animals' organic residues decomposed by *Musca domestica* and *Calliphora vomitaria* fly larvae. *J. Agric. Environ. Sci.* **6**(1): 92–104. doi:10.15640/jaes.v6n1a10.
- Bokossa, H.K.J., Saïdou, A., Fiogbé, E.D., and Kossou, D. 2014. Decomposition rate of pigs' manures and nutrient release pattern in wetland condition. *Agric. For. Fish.* **3**(4): 271–278.
- De Neve, S., Sleutel, S., and Hofman, G. 2003. Carbon mineralization from composts and food industry wastes added to soil. *Nutr. Cycl. Agroecosyst.* **67**: 13–20. doi:10.1023/A:1025113425069.
- Diener, S., Studd Solano, N.M., Roa Gutiérrez, F., Zurbrügg, C., and Tockner, K. 2011. Biological treatment of municipal organic waste using black soldier fly larvae. *Waste Biomass Valori.* **2**: 357–363. doi:10.1007/s12649-011-9079-1.
- Eghball, B. 2000. Nitrogen mineralization from field-applied beef cattle feedlot manure or compost. *Soil Sci. Soc. Am. J.* **64**: 2024–2030. doi:10.2136/sssaj2000.6462024x.
- Eghball, B., Wienhold, B.J., Gilley, J.E., and Eigenberg, R.A. 2002. Mineralization of manure nutrients. *Biol. Syst. Eng. Papers and Publications.* Paper 139.
- Erenstein, O., Gérard, B., and Tittonell, P. 2015. Biomass use trade-offs in cereal cropping systems: lessons and implications from the developing world. *Agric. Syst.* **134**: 1–5. doi:10.1016/j.agsy.2014.12.001.
- Flavel, T.C., and Murphy, D.V. 2006. Carbon and nitrogen mineralization rates after application of organic amendments to soil. *J. Environ. Qual.* **35**: 183–193. doi:10.2134/jeq2005.0022. PMID:16391289.
- Henin, S., and Dupuis, M. 1945. Essai de bilan de la matière organique du sol. *Ann. Agron.* **15**: 17–29.
- Hobbie, S.E. 2000. Interactions between litter lignin and soil nitrogen availability during leaf litter decomposition in a Hawaiian mountain forest. *Ecosystems*, **3**: 484–494. doi:10.1007/s100210000042.
- Huang, G.F., Wu, Q.T., Wong, J.W.C., and Nagar, B.B. 2006. Transformation of organic matter during co-composting of pig manure with sawdust. *Bioresour. Technol.* **97**: 1834–1842. doi:10.1016/j.biortech.2005.08.024. PMID:16289790.
- Igue, A.M., Saïdou, A., Adjanohoun, A., Ezui, G., Attiogbe, P., Kpagan, G., Gotoechan-Hodonou, H., Youl, S., Pare, T., Balogoun, I., Ouedraogo, J., Dossa, E., Mando, A., and Sogbedji, J.M. 2013. Evaluation de la fertilité des sols au Sud et au centre du Bénin. *Bull. Rech. Agron. Bénin, Spécial numéro, Fertilisation du maïs*, 12–23.
- Joffre, R., and Agren, G.I. 2001. From plant to soil: litter production and decomposition. Pages 83–99 in J. Roy, B. Saugier, and H.A. Mooney, eds. *Terrestrial global productivity*. Academic Press, New York, NY, USA.
- Kayuki, C.K., and Wortmann, S.C. 2001. Plant materials for soil fertility management in sub-humid tropical areas. *Agron. J.* **93**: 929–935. doi:10.2134/agronj2001.934929x.
- Keller, J.K., White, J.R., Bridgman, D.S., and Pastor, J. 2004. Climate change effects on carbon and nitrogen mineralization in peatlands through changes in soil quality. *Glob. Change Biol.* **10**: 10053–11064. doi:10.1111/j.1529-8817.2003.00785.x.
- Khalil, M.I., Hossain, M.B., and Schmidhalter, U. 2005. Carbon and nitrogen mineralization in different upland soils of subtropics treated with organic materials. *Soil Biol. Biochem.* **37**: 1507–1518. doi:10.1016/j.soilbio.2005.01.014.
- Lynch, D.H., Voroney, R.P., and Warman, P.R. 2005. Soil physical properties and organic matter fractions under forages receiving composts, manure or fertilizer. *Compost Sci. Util.* **13**: 252–261. doi:10.1080/1065657X.2005.10702249.
- Lynch, M.J., Mulvaney, M.J., Hodges, S.C., Thompson, T.L., and Thomason, W.E. 2016. Decomposition, nitrogen and carbon mineralization from food and cover crop residues in the central plateau of Haiti. *SpringerPlus*, **5**: 973. doi:10.1186/s40064-016-2651-1. PMID:27429883.
- Mader, P., Fliessbach, A., Dubois, D., Gunst, L., Fried, P., and Niggli, U. 2002. Soil fertility and biodiversity in organic farming. *Science*, **296**: 1694–1697. doi:10.1126/science.1071148. PMID:12040197.
- Matus, F.J., and Rodriguez, J. 1994. A simple model for estimating the contribution of nitrogen mineralization to nitrogen supply of crops from a stabilized pool of soil organic matter and recent organic input. *Plant Soil*, **162**: 259–271. doi:10.1007/BF01347713.
- N'Dayegamiye, A., Royer, R., and Audesse, P. 1997. Nitrogen mineralization and availability in manure composts from Québec biological farms. *Can. J. Soil Sci.* **77**(3): 345–350. doi:10.4141/S96-004.
- Nourbakhsh, F. 2007. Influence of vermicomposting on solid wastes decomposition kinetics in soils. *J. Zhejiang Univ. Sci.* **8**(10): 725–730. doi:10.1631/jzus.2007.B0725. PMID:17910115.
- Olson, J.S. 1963. Energy storage and the balance of producers and decomposers in ecological systems. *Ecology*, **44**: 322–331. doi:10.2307/1932179.
- Osono, T., Takeda, H., and Azuma, J.I. 2008. Lignin effects on carbon isotope dynamics during leaf litter decomposition in a cool temperate forest. *Ecol. Res.* **23**: 51–55. doi:10.1007/s11284-007-0336-5.
- Pandey, C., and Shukla, S. 2006. Effects of composted yard waste on water movement in sandy soil. *Compost Sci. Util.* **14**(4): 252–259. doi:10.1080/1065657X.2006.10702293.
- Parthasarathi, K., Balamurugan, M., and Ranganathan, L.S. 2008. Influence of vermicompost on the physico-chemical and biological properties in different types of soil along with yield and quality of the pulse crop—blackgram. *Iranian J. Environ. Health Sci. Eng.* **5**(1): 51–58.
- Pitta, C.S.R., Adami, P.F., Pelissari, A., Assmann, T.S., Franchin, M.F., Cassol, L.C., and Sartor, L.R. 2012. Year-round poultry litter decomposition and N, P, K and Ca release. *Braz. J. Soil Sci.* **36**: 1043–1053. doi:10.1590/S0100-06832012000300034.
- Powlson, D.S., Bhogal, A., Chambers, B.J., Coleman, K., Macdonald, A.J., Goulding, K.W.T., and Whitmore, A.P. 2012. The potential to increase soil carbon stocks through reduced tillage or organic material additions in England and Wales: a case study. *Agric. Ecosyst. Environ.* **146**: 23–33. doi:10.1016/j.agee.2011.10.004.
- Qiu, S., McComb, A.J., and Bell, R.W. 2012. Leaf litter decomposition and nutrient dynamics in woodland and wetland conditions along a forest to wetland hillslope. *Int. Schol. Res. Netw.* **8** pp. doi:10.5402/2012/346850.

- Saïdou, A., Janssen, B., and Temminghoff, E.J.M. 2003. Effects of soil properties, mulch and NPK fertiliser on maize yields and nutrient budgets on ferrallitic soils in southern Benin. *Agric. Ecosyst. Environ.* **100**: 265–273. doi:[10.1016/S0167-8809\(03\)00184-1](https://doi.org/10.1016/S0167-8809(03)00184-1).
- Saïdou, A., Bokossa, H.K.J., Fiogbé, E.D., and Kossou, D. 2016. Kinetic of pigs' manures decomposition and nutrient release pattern in ferrallitic soil of Benin (West Africa). *J. Soil Sci. Environ. Manag.* **7**(6): 73–80.
- Saïdou, A., Balogoun, I., Ahoton, E.L., Igué, A.M., Youl, S., and Ezui, G. 2017. Fertilizer recommendations for corn production in the South Sudan and Sudano-Guinean zones of Benin. *Nutr. Cycl. Agroecosyst.* **110**: 361–373. doi:[10.1007/s10705-017-9902-6](https://doi.org/10.1007/s10705-017-9902-6).
- Schjønning, P., Thomsen, I.K., Moldrup, P., and Christensen, B.T. 2003. Linking soil microbial activity to water-and air-phase contents and diffusivities. *Soil Sci. Soc. Am. J.* **67**: 156–165. doi:[10.2136/sssaj2003.1560](https://doi.org/10.2136/sssaj2003.1560).
- Singh, B.P., Rengel, Z., and Bowden, J.W. 2006. Carbon, nitrogen and sulphur cycling following incorporation of canola residue of different sizes into a nutrient-poor sandy soil. *Soil Biol. Biochem.* **38**: 32–42. doi:[10.1016/j.soilbio.2005.03.025](https://doi.org/10.1016/j.soilbio.2005.03.025).
- Spiess, A., and Neumeyer, N. 2010. An evaluation of  $R^2$ ; as an inadequate measure for nonlinear models in pharmacological and biochemical research: a Monte Carlo approach. *BMC Pharmacol.* **10**: 6. doi:[10.1186/1471-2210-10-6](https://doi.org/10.1186/1471-2210-10-6). PMID:[20529254](https://pubmed.ncbi.nlm.nih.gov/20529254/).
- Tan, Z.X., Lal, R., and Wiebe, K.D. 2005. Global soil nutrient depletion and yield reduction. *J. Sustain. Agric.* **26**: 123–146. doi:[10.1300/J064v26n01\\_10](https://doi.org/10.1300/J064v26n01_10).
- Tian, G., Kang, B.T., and Brussaard, L. 1992. Biological effects of plant residues with contrasting chemical composition under humid tropical conditions decomposition and nutrient release. *Soil Biol. Biochem.* **24**: 1051–1060. doi:[10.1016/0038-0717\(92\)90035-V](https://doi.org/10.1016/0038-0717(92)90035-V).
- United States Department of Agriculture (USDA). 1998. Keys to soil taxonomy. 8th ed. Soil Survey Staff, USDA–NRCS, Washington, USA.
- Wang, H., Wang, S., Li, H., Wang, B., Zhou, Q., Zhang, X., Li, J., and Zhang, Z. 2016. Decomposition and humification of dissolved organic matter in swine manure during housefly larvae composting. *Waste Manag. Res.* **34**(5): 465–473. doi:[10.1177/0734242X16636675](https://doi.org/10.1177/0734242X16636675). PMID:[26987735](https://pubmed.ncbi.nlm.nih.gov/26987735/).
- Whalen, J.K., Chang, C., and Olson, B.M., 2001. Nitrogen and phosphorus mineralization potentials of soils receiving repeated annual cattle manure applications. *Biol. Fertil. Soil*, **34**: 334–341. doi:[10.1007/s003740100416](https://doi.org/10.1007/s003740100416).
- Yang, H.S. 1996. Modelling organic matter mineralization and exploring options for organic matter management in arable farming in Northern China. PhD thesis, Landbouwniversiteit, Wageningen, the Netherlands. 159 pp.
- Yang, H.S., and Janssen, B.H. 2000. A mono-component model of carbon mineralization with a dynamic rate constant. *Eur. J. Soil Sci.* **51**: 517–529. doi:[10.1046/j.1365-2389.2000.00319.x](https://doi.org/10.1046/j.1365-2389.2000.00319.x).
- Yusuf, A.A., Iwuafor, E.N.O., Abaidoo, R.C., Olufajo, O.O., and Sanginga, N. 2009. Grain legume rotation benefits to maize in northern Guinea savanna of Nigeria: fixed-nitrogen versus other rotation effects. *Nutr. Cycl. Agroecosyst.* **84**: 129–139. doi:[10.1007/s10705-008-9232-9](https://doi.org/10.1007/s10705-008-9232-9).
- Zhang, H.J., and Mastudo, T. 2011. Comparison of mass balance, energy consumption and cost of composting facilities for different types of organic waste. *Waste Manag.* **31**: 416–422. doi:[10.1016/j.wasman.2010.09.010](https://doi.org/10.1016/j.wasman.2010.09.010). PMID:[20951564](https://pubmed.ncbi.nlm.nih.gov/20951564/).
- Zhang, Z., Wang, H., Jun Zhu, J., Suneethi, S., and Zheng, J. 2012. Swine manure vermicomposting via housefly larvae (*Musca domestica*): the dynamics of biochemical and microbial features. *Bioresour. Technol.* **118**: 563–571. doi:[10.1016/j.biortech.2012.05.048](https://doi.org/10.1016/j.biortech.2012.05.048). PMID:[22728759](https://pubmed.ncbi.nlm.nih.gov/22728759/).
- Zhang, Z.J., Shen, J., and Wang, H. 2014. Attenuation of veterinary antibiotics in full-scale vermicomposting of swine manure via the housefly larvae (*Musca domestica*). *Sci. Rep.* **4**: 6844. doi:[10.1038/srep06844](https://doi.org/10.1038/srep06844). PMID:[25354896](https://pubmed.ncbi.nlm.nih.gov/25354896/).
- Zhu, F., Wang, W., Hong, C., Feng, M., Xue, Z., Chen, X., Yao, Y., and Yu, M. 2012. Rapid production of maggots as feed supplement and organic fertilizer by the two-stage composting of pig manure. *Bioresour. Technol.* **116**: 485–491. doi:[10.1016/j.biortech.2012.04.008](https://doi.org/10.1016/j.biortech.2012.04.008). PMID:[22541952](https://pubmed.ncbi.nlm.nih.gov/22541952/).
- Zhu, F., Yao, Y., Wang, S., Du, R., Wang, W., Chen, X., Hong, C., Qi, B., Xue, Z., and Yang, H. 2015. Housefly maggot-treated composting as sustainable option for pig manure management. *Waste Manag.* **35**: 62–67. doi:[10.1016/j.wasman.2014.10.005](https://doi.org/10.1016/j.wasman.2014.10.005). PMID:[25458853](https://pubmed.ncbi.nlm.nih.gov/25458853/).