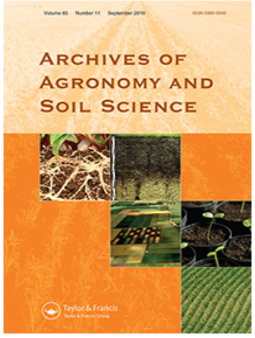

Taylor & Francis
Taylor & Francis Group

Archives of Agronomy and Soil Science

ISSN: 0365-0340 (Print) 1476-3567 (Online) Journal homepage: https://www.tandfonline.com/loi/gags20

Decomposition and nutrient release pattern of agro-processing by-products biodegraded by fly larvae in Acrisols

Bloukounon-Goubalan Adin Yéton, Saïdou Aliou, Obognon Noël, Amadji Guillaume Lucien, Igué Attanda Mouinou, Clottey Victor Attuquaye, Chrysostome Christophe Achille Armand Mahussi, Kenis Marc & Mensah Guy Apollinaire

ARCHIVES OF AGRONOMY AND SOIL SCIENCE
2019, VOL. 65, NO. 11, 1610–1621
https://doi.org/10.1080/03650340.2019.1572118

Decomposition and nutrient release pattern of agro-processing by-products biodegraded by fly larvae in Acrisols

Bloukounon-Goubalan Adin Yéton[a], Saïdou Aliou[a], Obognon Noël[a], Amadji Guillaume Lucien[b], Igué Attanda Mouinou[c], Clottey Victor Attuquaye[d], Chrysostome Christophe Achille Armand Mahussi[e], Kenis Marc[f] and Mensah Guy Apollinaire[c]

[a]Integrated Soil and Crops Management (ISCM) Research Unit, Laboratory of Soil Sciences, School of Crop Science, Faculty of Agronomic Sciences, University of Abomey-Calavi, Abomey-Calavi, Benin; [b]Eco-Pedology Research Center, Laboratory of Soil Sciences, School of Crop Science, Faculty of Agronomic Sciences, University of Abomey-Calavi, Abomey-Calavi, Benin; [c]Laboratory of Zootechnology, Veterinary and Fishery Research, CRA Agonkanmey, National Institute of Agriculture Researches, Abomey-Calavi, Benin; [d]CABI, CSIR Campus, No.6 Agostino Neto Road, Airport Residential Area, Cantonments, Ghana; [e]Laboratory of Aviculture and Zoo-Economic Research, School of Animal Production, Faculty of Agronomic Sciences, University of Abomey-Calavi, Abomey-Calavi, Benin; [f]CABI, Rue des Grillons 1, Delémont, 2800, Switzerland

ABSTRACT

Fly larvae are increasingly being promoted as animal feed and their production on agro-processing by-products generates a high amount of residues. Understanding the decomposition and nutrients release pattern in the soil of these residues is of importance to evaluate their quality as soil amendment. A litter bag experiment was carried out over 75 days in southern Benin with corn bran, a mixture of soybean bran and corn bran and a mixture of soybean bran and corn hull, all biodegraded in advance by larvae of *Musca domestica* and *Hermetia illucens*. Bags with 200 g dry matter of each residue were buried in the soil. The first order equation of mono-component model $Y_t = Y_0 \times e^{-kt}$ was suitable and described well the decomposition and mineralization pattern of the residues. The residues decomposed quickly and released nutrients readily into the soil. The mass remaining at the end of the decomposition process ranged between 38% and 42% of the initial weight. The half-life of the organic carbon in the residues ranged between 50 and 58 days. Organic nitrogen mineralized fast, with rates ranging between 0.007 and 0.011 day^{-1}. These organic residues can be used as soil amendments to improve crop productivity in an Acrisol.

ARTICLE HISTORY
Received 28 April 2018
Accepted 16 January 2019

KEYWORDS
Organic residue; modelling; mineralization pattern; soil fertility; southern Benin

Introduction

The supply of organic residues to soils is recognized as a sustainable strategy for soil fertility replenishment in Sub-Saharan Africa. Organic residues provide carbon as energy source for soil microorganisms, increase microbial activity and play an important role due to their short-term effect on nutrient supply to crops (Palm et al. 2001). Wastes from a number of food industry sources are potentially valuable resources in agriculture, both for nutrient supply and for replenishing soil organic matter (De Neve et al. 2003). In Benin, many agro-processing by-products are

CONTACT Bloukounon-Goubalan Adin Yéton adinbloukounon@gmail.com Integrated Soil and Crops Management (ISCM) Research Unit, Laboratory of Soil Sciences, School of Crop Science, Faculty of Agronomic Sciences, University of Abomey-Calavi, Abomey-Calavi, Benin

created at the household level and also by women's groups. These include residues such as soybean bran, corn bran and sorghum bran, which are often thrown away. These wastes contain high concentrations of nitrogen, cellulose, hemicellulose, and lignin (Rose et al. 2010) and, thus, could be used as soil amendment. However, these residues must first be transformed to obtain mature and stabilized organic matter.

Fly larvae, mainly house fly (*Musca domestica* L.) and black soldier fly (*Hermetia illucens* (L.)) are increasingly being promoted as protein sources for poultry and fish feed, both at farm level and for industrial protein production (Kenis et al. 2014; Pastor et al. 2015; Pomalégni et al. 2017). In Benin, around 4–6% of the farmers produce house fly larvae by exposing various animal and plant wastes to naturally occurring house flies (Bloukounon-Goubalan et al. 2017; Pomalégni et al. 2017). The production of fly larvae generates a high amount of residues that should be re-used in agriculture for increasing the profitability of the system (Kenis et al. 2018). Fly larvae easily degrade organic material of different origins such as domestic waste, poultry, pig, and cow manure and even human excreta leading to a more stable and mature bio-product (Diener et al. 2011; Banks et al. 2014; Wang et al. 2016). The biodegradation of the agro-processing by-products by the fly larvae results in some physical and chemical changes leading to mature enough bio-products (Bloukounon-Goubalan et al. 2019). Nonetheless, a better knowledge of the decomposition and nutrients mineralization dynamics of the agro-processing by-products biodegraded by fly larvae is essential to assess the potential of these residues for soil fertility restoration. For instance, the rate of nitrogen mineralization of organic materials in soil depends on their chemical composition, the origin and transformation of the organic materials, the method of composting and also the soil environmental conditions (Antil et al. 2011).

Numerous researches had been carried out on the decomposition and nutrients release pattern of compost and vermicompost from different sources of organic residues (Cambardella et al. 2003; De Neve et al. 2003; Griffin and Hutchinson 2013). However, little information on the decomposition and nutrients' mineralization of the organic residues biodegraded by fly larvae is available. Also, no study has been carried out yet on the nutrient release pattern of agro-processing by-products biodegraded by fly larvae in an Acrisol in sub-Saharan Africa. Knowing the kinetics of the mineralization process will allow quantifying the amount of organic manure to be supplied or to predict organic matter dynamics in the soil in order to enhance crop production (Saïdou et al. 2016).

This paper aims to assess the decomposition and the mineralization rates of agro-processing by-products biodegraded by fly larvae under field conditions. Specifically, it aims at i) assessing the suitable model for decomposition and nutrients mineralization of agro-processing by-products biodegraded by the fly larvae; ii) assessing the kinetics of the decomposition process and nutrients release pattern of these by-products in an Acrisol.

Material and methods

Study areas

The experiment was carried out at the experimental site of the Faculty of Agronomic Sciences of the University of Abomey-Calavi, located at Sékou, district of Allada, southern Benin from August to October 2017. The study area is located on longitude 002°14'308 E and latitude 06°37'484 N at an altitude of 175 m above sea level. The site received 306 mm rainfall during the period of the experiment. Monthly maximum temperatures ranged between 28 °C and 30 °C. Figure 1 presents the rainfall distribution during 2017. The soil is classified as Acrisol (FAO (Food and Agriculture Organization of the United Nations) 2006).

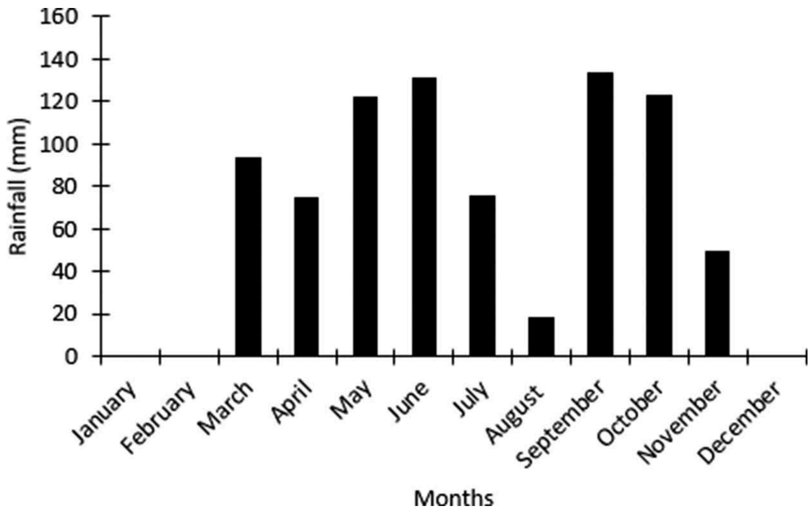

Figure 1. Rainfall distribution in the study area in 2017. Bars represent the total rainfall of the month.

Biodegradation of the substrates by fly larvae

The agro-processing by-products biodegraded by fly larvae used for the experiment were corn bran; a mixture of soybean bran and corn bran (1:1 ratio) and a mixture of soybean bran and corn hull (8:2 ratio). The biodegradation process was performed by *Musca domestica* larvae during the first 12 days and by *Hermetia illucens* larvae from day 5 to 30. In fact, due the growth cycle of the flies, the biodegradation process was subdivided into four stages. During the first stage, a quantity of 3 kg of each type of substrate (65% to 75% moisture content) was weighed in a plastic container and placed in an aerated shed for oviposition by naturally occurring adults of *M. domestica* and *H. illucens*. After four days of biodegradation by the *M. domestica*, the larvae were removed from the substrate with a sieve in order to avoid pupation. The remaining residue in each container was replenished with 1 kg of additional fresh substrate for the second stage of a four-day biodegradation process and this was repeated for a third stage. *Hermetia illucens* larvae, which grow much slower than *M. domestica*, appeared in the substrates on day 4. Thus, when sieving the *M. domestica* larvae, the *H. illucens* larvae are left in the substrate. At the end of the third stage, the substrates were left solely to *Hermetia illucens* for the final biodegradation until day 30, when the cycle was completed (Myers et al. 2008). Nutrients dynamic in the substrates during the biodegradation process are presented in Table 1.

Table 1. Nutrient dynamics in the substrates during the biodegradation by fly larvae.

Nutrients	Substrates	Day 1	Day 4	Day 12	Day 30
Carbon (g kg^{-1})	Mixture of soybean bran and corn hull	548.4 ± 1.6	546.0 ± 1.2	534.3 ± 0.2	497.3 ± 5.5
	Corn bran	552.4 ± 1.8	545.3 ± 2.2	566.1 ± 0.3	557 ± 4.3
	Mixture of soybean bran and corn bran	548.5 ± 0.3	544.5 ± 0.4	548.5 ± 2.9	525.9 ± 1.3
Nitrogen (g kg^{-1})	Mixture of soybean bran and corn hull	73.8 ± 0.9	65.3 ± 1.0	64.3 ± 1.5	61.8 ± 0.0
	Corn bran	72.1 ± 1.0	63.5 ± 1.0	66.5 ± 0.9	61.9 ± 0.1
	Mixture of soybean bran and corn bran	71.6 ± 0.6	63.4 ± 0.1	61.9 ± 1.3	60.8 ± 0.1
NH_4-N (g kg^{-1})	Mixture of soybean bran and corn hull	12.7 ± 0.4	7.9 ± 0.5	6.0 ± 0.0	4.6 ± 0.1
	Corn bran	12.9 ± 0.9	6.2 ± 0.0	13.3 ± 0.1	10.3 ± 0.2
	Mixture of soybean bran and corn bran	16.4 ± 0.9	10.5 ± 0.8	10.8 ± 0.6	9.2 ± 0.7
NO_3-N (g kg^{-1})	Mixture of soybean bran and corn hull	4.6 ± 0.2	3.2 ± 0.1	1.7 ± 0.3	1.6 ± 0.1
	Corn bran	6.5 ± 0.2	3.8 ± 0.1	2.0 ± 0.3	5.1 ± 0.2
	Mixture of soybean bran and corn bran	4.9 ± 0.1	3.4 ± 0.2	1.5 ± 0.2	5.1 ± 0.1

Experimental design and decomposition process in the soil

The residues collected at the end of the 30 days of biodegradation were dried at 65 °C. Two hundred g of the dry residues were placed into a 20 × 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 residue for a replicate were constituted in order to process a removal samples at 15, 30, 45, 60 and 75 days of decomposition in the soil, leading to 120 nylon-meshed bags with residues buried in the soil at 15 cm depth and 2 m between replicates and blocks. At each sampling date, the remaining residue in a sampled bag is oven dried at 65 °C and weighed to determine the remaining mass after decomposition in the soil. Samples of experimental soil, each initial residue and the remaining residue at each sampling date were analyzed for their nutrients content.

Chemical analyses of the residues and experimental soil

The samples of residues were analyzed at the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) laboratory at Niamey, Niger for organic carbon, total nitrogen, total phosphorus, total potassium, total calcium, and total magnesium. Then, during the biodegradation by fly larvae, the substrates were sampled and analyzed for organic carbon, total and mineral nitrogen. Experimental soil was sampled before trial and analyzed at the Laboratory of soil science Water and Environment of National Institute of Agriculture Researches of Benin for organic carbon, available phosphorus, exchangeable bases, and cation exchangeable capacity (CEC).

Organic carbon was determined according to Walkley and Black wet oxidation method. Concentrated H_2SO_4 was added to a mixture of sample and 1 N $K_2Cr_2O_7$ solution leading to oxidation of organic matter. The residual dichromate was titrated against iron sulfate. Then, after digestion in a mixture of concentrated sulfuric acid (H_2SO_4), salicylic acid ($C_7H_6O_3$), hydrogen peroxide (H_2O_2) and selenium as a catalyst by heating to about 330 °C for 3 hrs, total P was measured by spectrophotometry in ammonium molybdate solution with ascorbic acid at a wavelength of 660 nm. Available phosphorus was measured by Bray 1 method. Determination of total N was carried out from the same digest by spectrophotometry with auto-Analyzer using Berthelot reaction; ammoniac ($N\text{-}NH_4^+$) and nitrate ($N\text{-}NO_3^-$) in the substrates during the biodegradation by fly larvae in 0.01 M $CaCl_2$ method. From the same digest, K, Ca and Mg were determined by atomic absorption spectrophotometry using Perkin-Elmer model Analyst 400. Then, after extraction by 1 N ammonium acetate at pH 7 method, exchangeable potassium was determined by a flame photometer, and CEC by colorimetry by the determination of NH_4-N in the KCl extract.

Data analysis

Statistical differences in substrates and between decomposition period were determined using the linear model function of an analysis of variance in R 3.0.2 software and a Student Newman-Keuls test at $\alpha = 0.05$. Several models (linear, parametric and exponential) were tested for the best R^2. The first order equation of mono-component model with a constant mineralization rate proposed by Henin and Dupuis (1945) provided the best R^2 and was fitted using Equation 1. Adjusted R^2 was used for judging the fit between model and observation using the most general definition (Anderson-Sprecher 1994; Yang 1996; Spiess and Neumeyer 2010). The half-life values of the residue decomposition and mineralization were calculated from Equation 2 suggested by Olson (1963).

$$Y_t = Y_0{}^x e^{-kt} \tag{1}$$

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

where Y_0 is the percentage of weight or nutrient remaining in the residues, respectively, at time t and 0, k is the mineralization rate. For testing the models described above, the significance of k and Y_0 was checked.

Results

Chemical characteristics of experimental soil and residues

Soil was slightly acidic, low in organic matter content and low in total nitrogen. It was also deficient in available phosphorus and exchangeable bases with low cation exchangeable capacity (Table 2). This soil requires organic amendment for sustaining crop production. The corn bran residue had the highest concentration of organic carbon and the highest C:N ratio (Table 1). The residue from the mixture of soybean bran and corn hull had the highest levels in P, K, Ca and Mg (Table 3).

Decomposition pattern of the different residues in the soil

The Residues' decomposition differed significantly ($p < 0.05$, Figure 2). After 15 days in the soil, the weight loss in the residues was similar ($p > 0.05$) according to the Student Newman-Keuls test. But after 30 till 45 days in the soil, the weight loss in the residues was significantly different ($p < 0.05$) and was on average two times higher in the residue from corn bran and the mixture of soybean bran and corn bran than the loss in the mixture of soybean bran and corn hull. The total weight loss during the entire decomposition period was highest in the residue from corn bran and the mixture of soybean bran and corn hull and lowest in the residue from the mixture of soybean bran and corn bran. The maximum amount of weight loss was recorded between day 15 and day 30 in the residue from corn bran and the mixture of soybean bran and corn bran and between day 45 and day 60 in the residue from the mixture of soybean bran and corn hull.

Table 2. Average values of soil chemical properties before starting the experiment.

Soil characteristics	Means ± standard errors
pH (water)	6.1 ± 0.6
pH (KCl)	4.4 ± 0.1
Organic matter (g kg^{-1})	14.3 ± 0.2
Total nitrogen (g kg^{-1})	0.9 ± 0.0
Available phosphorus (mg kg^{-1})	9.6 ± 1.0
Exchangeable K (cmol kg^{-1})	0.1 ± 0.0
Exchangeable Ca (cmol kg^{-1})	1.5 ± 0.0
Exchangeable Mg (cmol kg^{-1})	0.7 ± 0.0
CEC (cmol kg^{-1})	6.8 ± 0.1

Table 3. Chemical concentration in the different types of residues after biodegradation and before starting the experiment.

	Concentration of Agro-processing by-products (g kg^{-1})		
Chemical elements	Mixture of soybean bran and corn hull	Corn bran	Mixture of soybean bran and corn bran
P	13.0 ± 0.1a	5.3 ± 0.1c	7.4 ± 0.3b
K	36.9 ± 0.4a	2.6 ± 0.1c	14 ± 0.2b
Ca	10.3 ± 0.1a	1.2 ± 0.1c	6.4 ± 0.2b
Mg	5.5 ± 0.3a	0.7 ± 0.1c	2.4 ± 0.1b

Means with the same alphabet are not significantly different at $p > 0.05$ according to the Newman-Keuls test.

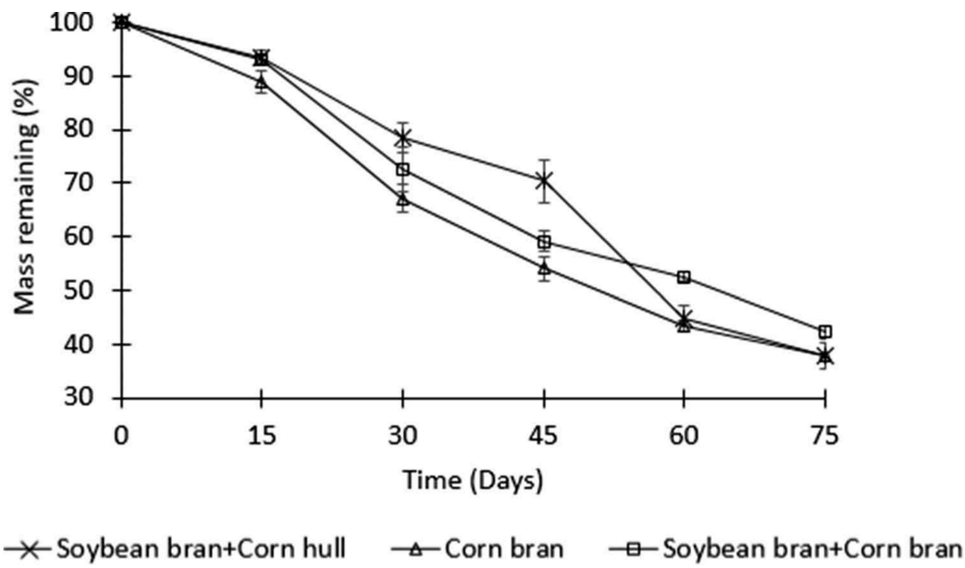

Figure 2. Decomposition pattern of the different types of substrate previously biodegraded by the fly larvae.

Table 4. Exponential functions describing weight and nutrients remaining after decomposition in the soil of the different residues.

Residues	Parameters	Fitted models	Adjusted-R^2	Half-life period $t_{0.5}$ in fifteen days
Mixture of soybean bran and corn hull	Mass remaining	$Y_t = 106.22e^{-0.180t}$	0.91	3.85***
	C	$Y_t = 105.16e^{-0.209t}$	0.94	3.32**
	N	$Y_t = 103.18e^{-0.163t}$	0.96	4.25***
	P	$Y_t = 101.84e^{-0.086t}$	0.98	8.06***
	K	$Y_t = 104.54e^{-0.206t}$	0.96	3.36***
	Ca	$Y_t = 104.99e^{-0.171t}$	0.92	4.05**
	Mg	$Y_t = 106.14e^{-0.166t}$	0.92	4.17**
Corn bran	Mass remaining	$Y_t = 102.67e^{-0.206t}$	0.98	3.36***
	C	$Y_t = 102.52e^{-0.194t}$	0.96	3.57***
	N	$Y_t = 105.03e^{-0.119t}$	0.91	5.82**
	P	$Y_t = 101.66e^{-0.118t}$	0.97	5.87***
	K	$Y_t = 102.51e^{-0.183t}$	0.98	3.79***
	Ca	$Y_t = 107.73e^{-0.274t}$	0.92	2.53**
	Mg	$Y_t = 110.21e^{-0.270t}$	0.87	2.57**
Mixture of soybean bran and corn bran	Mass remaining	$Y_t = 103.45e^{-0.174t}$	0.97	3.98***
	C	$Y_t = 103.01e^{-0.178t}$	0.93	3.89**
	N	$Y_t = 101.42e^{-0.105t}$	0.95	6.60***
	P	$Y_t = 101.52e^{-0.150t}$	0.99	4.62***
	K	$Y_t = 105.79e^{-0.180t}$	0.95	3.85**
	Ca	$Y_t = 102.00e^{-0.081t}$	0.98	8.56***
	Mg	$Y_t = 100.12e^{-0.088t}$	1.00	7.88***

*** $p < 0.001$; ** $p < 0.01$; Y: Mass fraction of the remaining residue or nutrient (%) in a residue at a specific time (t in 15 days).

Kinetic of the decomposition of the residues and nutrients mineralization in the soil

The exponential mono-component model fitted well to the decomposition of each residue and the mineralization of nutrients (Table 4). In the model, the organic residue is considered as a whole with constant mineralization rate, k. The model indicated that weight and nutrients remaining in each residue at the time t were a function of the initial nutrient content and the rate constant. The adjusted R^2 ranged between 0.87 and 1.00. The decomposition rates of each residue ranged between 0.011 and 0.014 day^{-1} and were fastest in the residue from corn bran.

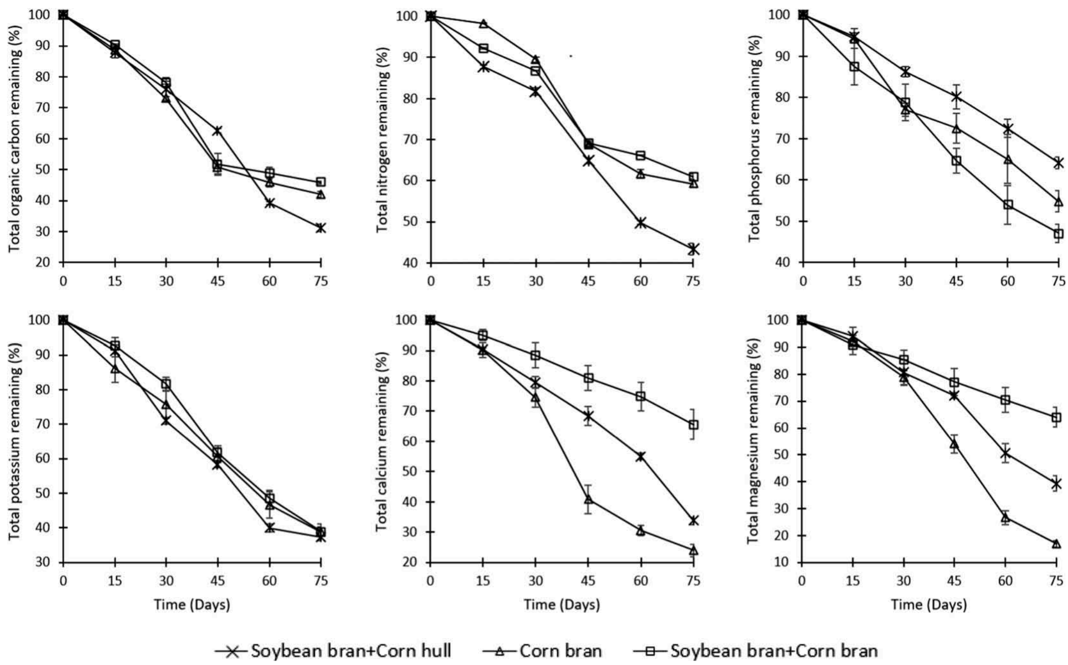

Figure 3. Change in the nutrients' content in the residues during the mineralization process.

The half-life of the residues ranged between 50 and 60 days and was slightly similar in the mixture of soybean bran and corn hull (58 days) and in the mixture of soybean bran and corn bran (60 days).

Generally, organic carbon decomposition followed the same trend as residue weight. The fraction of organic carbon mineralized after 75 days of decomposition was between 54% and 69% (Figure 3).

Nutrient contents in the residues decreased significantly ($p < 0.05$) during the mineralization process (Figure 3). Organic nitrogen mineralized faster in the residue from the mixture of soybean bran and corn hull (0.011 day^{-1}) than in that of corn bran (0.008 day^{-1}) and in the mixture of soybean bran and corn bran (0.007 day^{-1}). Fifty percentage N releases were attained after 64, 84 and 99 days in the residues from the mixture of soybean bran and corn hull, the corn bran and the mixture of soybean bran and corn bran, respectively. Generally, the release of P during the mineralization period was close to nitrogen in all residues. The percentage of P mineralized during the decomposition period was highest in the residue from the mixture of soybean bran and corn hull and the mixture of soybean bran and corn bran and lowest in the residue from corn bran. The half-life of the residues' organic phosphorus was on average 92 days. Potassium mineralization rate ranged between 0.012 and 0.014 day^{-1} and was higher compared to nitrogen and phosphorus. The percentage of K mineralized during the experiment was almost similar in the different residues. The mineralization rates of calcium and magnesium in the residue from corn bran ($k = 0.018$ day^{-1}) were higher than the other residues. Calcium and magnesium mineralization rates in the residue from corn bran were three times higher than in those of the mixture of soybean bran and corn bran and two times higher than in the mixture of soybean bran and corn hull. In general, nutrients' mineralization increased in the order P < N < Mg < Ca < K (in the residue from the mixture of soybean bran and corn hull), P < N < K < Mg < Ca (in the residue from corn bran) and Ca < Mg < N < P < K (in the residue from the mixture of soybean bran and corn bran).

Discussion

Suitability of the first order of mono-component model to predict decomposition and mineralization of the agro-processing by-products biodegraded by fly larvae

The decomposition and the mineralization of the studied residues are best described by the single exponential model $Y_t = Y_0 \times e^{-kt}$. This model is commonly used and fits well for a variety of litters, compost, and other organic residues (N'Dayegamiye et al. 1997; Dhanya et al. 2013; Saïdou et al. 2016). The basic assumption is that k is constant. According to Aber et al. (1990), this model works reasonably well until 20% of the initial mass remains. Unlike the single exponential model, quadratic and power models have been used to explain the dynamics in the residues with some components, i.e. the rapid degrading components such as carbohydrates, hemicelluloses, water-soluble and the slower degrading components such as waxes, lignin, suberins (Rovira and Vallejo 2000; Rovira and Rovira 2010). Thus, the single exponential model fits well to describe the dynamic of the studied residues.

Decomposition of the agro-processing by-products biodegraded by fly larvae in soil

Few studies on the decomposition of agro-processing by-products in soil are available and none on the decomposition of substrates previously biodegraded by fly larvae. Substrate weight loss with time is typically used to determine decomposition rates. The decomposition rate of the residues used in these experiments (from 0.011 to 0.013 day^{-1}) was almost similar to those recorded in green manure (Thonnissen et al. 2000) and *Acacia mangium* litter (Cattanio et al. 2008) but was higher than the decomposition rate of 0.005 day^{-1} observed with pig manure (Saïdou et al. 2016) and the rate of 0.057 week^{-1} in wheat crops residues (Rezig et al. 2014). Pitta et al. (2012) found that less than 50% of the poultry litter was decomposed within 90 days in the fields. In the present study, more than 60% of the initial mass of the biodegraded agro-processing by-products was decomposed after 75 days in the soil. Our results confirmed the short-term residual effect of the agro-processing by-products in the soil. Generally, weight loss followed the same trend as organic carbon mineralization. Several studies reported a rapid organic carbon mineralization in fresh manure and a lower one in composts, due to the stability of composts. De Neve et al. (2003) found less than 10% of organic carbon mineralized in different composts after six weeks in the soil. Similarly, Cattanio et al. (2008) found less than 50% of organic carbon mineralized in different leguminous plant wastes after 100 days in soil and Saïdou et al. (2016) found also less than 10% of organic carbon mineralized in fresh pig manure after 90 days in soil. In this study, the organic carbon released by the agro-processing by-products biodegraded by fly larvae, ranged between 54% and 69% after 75 days, was higher than those of some mineralization studies. According to Bernal et al. (2009), any compost in which more than 30% of organic carbon mineralizes after 70 days indicates an immature material. Also, immature composts may contain high amounts of free ammonia (Bernal et al. 2009). Bloukounon-Goubalan et al. (2019) found NH_4-N content up to 10 g kg^{-1} in the agro-processing by-products after the biodegradation by fly larvae. Our findings point out that the agro-processing by-products biodegraded by fly larvae did not reach their maturity and would need additional transformation. Immature material can lead to emission of odors and continued active decomposition when added to soil and then can inhibit seed germination, reduce plant growth and damage crops by competing for oxygen or causing phytotoxicity due to insufficient decomposition of organic matter (Brewer and Sullivan 2003; Huang et al. 2004) and the development of toxic compounds. However, several studies hypothesize an interrelation between fly larvae activity and micro-organisms in the substrates during the biodegradation process (Čičková et al. 2015; Bloukounon-Goubalan et al. 2017). As a matter of fact, the fly larvae activity favors the growth of aerobic microorganisms by increasing water and ammonia losses through mechanical aeration. For that, we suggest leaving the biodegraded substrates for few days before applying them to soil in order to increase their maturity and stability with the aid of the activity of micro-organisms present in the material.

The half-life of the residues organic carbon ranged between 50 and 58 days, suggesting that they could support soil organism activity in the short-term but not in the long-term. However, these residues can be used in the composting process as N sources.

Implications of nutrients mineralization of the agro-processing by-products biodegraded by fly larvae

Initial nitrogen content was high (average 6%) in the residues. This will reduce the risk of nitrogen immobilization in soil. Composted organic materials release nitrogen at rates considered to be slow (1–3% of total N per year), and the leaching process can extend for many years as long as the composted organic materials are decomposing (Al-Bataina et al. 2016). Nitrogen mineralization rate in the residues was between 0.7% and 1.1% of total N per day. This result shows that the studied residues can support plant N requirement at least during the first season crop. Thus, they can be considered as an effective N source for horticultural crops. Masunga et al. (2016) reported that high-quality organic inputs are characterized by a low C:N ratio and sufficient nitrogen to sustain microbes and crop growth. However, they may not contribute much to the maintenance of soil organic matter (Wang et al. 2004). Mineralization is high when the soil moisture content is near field capacity and declines in dry soil (Guntiñas et al. 2012). The experiment was performed during the short rainy season in which field capacity was not reached. Thus, the nitrogen mineralization of the residues could have been higher if the experiment had been carried out during the long rain season or under irrigation. Consequently, the risk of nitrogen loss would have increased under those conditions. The rapid nitrogen mineralization in the residues from the mixture of soybean bran and corn hull is not due to its nitrogen content which was not significantly different with that of residue from corn bran but probably rather to the lignin content, which is lower in soybean than in corn bran (Bellaloui 2002).

Results showed that nitrogen mineralization rate is close to the release of phosphorus. It is known that residues with low C:N and C:P ratios, a sufficient N:P ratio, and low lignin content decompose faster and release more P during the decomposition process (Silver and Miya 2001). Previous research under similar conditions with pig manure showed that phosphorus mineralization rates were not higher than 0.006 day^{-1} (Saïdou et al. 2016). Our results indicate that phosphorus was rapidly released in the residues from corn bran and the mixture of soybean bran and corn bran. Mineralization of organic phosphorus may be of great importance for plant nutrition in soils containing low amounts of available phosphorus. This could be advantageous for microorganisms and plant growth. In fact, the incorporation of phosphorus into microbial cells prevents its strong sorption to soil iron and aluminum oxides and hydroxide by maintaining it in a form that can be released subsequently into the soil solution following microbial turnover. This is an interesting result as Acrisols are known for their low available P content (Saïdou et al. 2017) due to the fact that major portions of the ion exchange complex of these soils are formed by iron and aluminum oxides and hydroxides responsible for P fixation.

In all residues, potassium was more rapidly released than nitrogen and phosphorus. But the leaching risk is very low as it is absorbed by the soil particles (Ayeni and Adeleye 2014). The rapid release of potassium from plants' residues relative to nitrogen and phosphorus is a common observation (Semwal et al. 2003; Njunie et al. 2004; Bayala et al. 2005) and due to the fact that potassium is not a structural component of plants and is therefore susceptible to leaching from decomposing plants residues (Lupwayi et al. 2006). The high amount (62%) of potassium released after 75 days decomposition in the soil proves that the residues are suitable for crops production especially root vegetables and fruits, which require high amounts of potassium.

Calcium and magnesium were more rapidly released in the residue from corn bran although this residue had a lower amount of these two nutrients. Thus, mineralization was not much affected by nutrients concentrations in the residues. The high amount of calcium and magnesium released till 75 days in the soil was probably due to the different transformations that occurred during the biodegradation process by fly larvae. In fact, the oxygen supplied through aeration during the biodegradation process by fly larvae stimulates micro-organisms to convert organic compounds into inorganic ones (Čičková et al. 2015). These transformations could have led to a quick calcium and magnesium release, which are very mobile in their inorganic form. That could be a disadvantage for the plants since calcium and magnesium will probably be lost through leaching.

Conclusion

The present study shows that 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. Corn bran, the mixture of soybean bran and corn bran, the mixture of soybean bran and corn hull biodegraded by fly larvae contain a sufficient quantity of nitrogen and could be an effective nitrogen source for vegetable production. But, the rapid decomposition and mineralization of organic carbon and nutrients show that the residues are less stable and immature than a number of organic materials used as soil amendment. The short half-life of the residues suggests that they could support soil organism activity in the short-term but not in the long-term. The study suggests using these residues as N source in compost or leaving the biodegraded substrates for few days to mature before using as soil amendment.

Acknowledgments

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). MK 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).

Disclosure statement

No potential conflict of interest was reported by the authors.

Funding

This work was supported 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).

References

Aber JD, Melillo JM, MacClaugherty CA. 1990. Predicting long-term patterns of mass loss, N dynamics, and soil organic matter formation from initial fine litter chemistry in temperate forest ecosystems. Can J Bot. 68:2201–2208. doi:10.1139/b90-287.

Al-Bataina BB, Young MT, Ranieri E. 2016. Effects of compost age on the release of nutrients. Int Soil Water Conserv Res. 4:230–236. doi:10.1016/j.iswcr.2016.07.003.

Anderson-Sprecher R. 1994. Model comparisons and R^2. Am Stat. 48:113–117.

Antil RS, Bar-Tal A, Fine P, Hadas A. 2011. Predicting Nitrogen and carbon mineralization of composted manure and sewage sludge in soil. Compost Sci Util. 19:33–43. doi:10.1080/1065657X.2011.10736974.

Ayeni LS, Adeleye OE. 2014. Mineralization rates of soil forms of nitrogen, phosphorus, and potassium as affected by organomineral fertilizer in sandy loam. Adv Agron. 2014:5 p.

Banks IJ, Gibson WT, Cameron MM. 2014. Growth rates of black soldier fly larvae fed on fresh human faeces and their implication for improving sanitation. Trop Med Int Health. 19(1):14–22. doi:10.1111/tmi.12251.

Bayala J, Mando A, Teklehaimanot Z, Ouedraogo SJ. 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.

Bellaloui N. 2002. Soybean seed phenol, lignin, and isoflavones partitioning as affected by seed node position and genotype differences. Food Nutr Sci. 3:447–454.

Bernal MP, Alburquerque JA, Moral R. 2009. Composting of animal manures and chemical criteria for compost maturity assessment. Rev Bioresour Technol. 100:5444–5453. doi:10.1016/j.biortech.2008.11.027.

Bloukounon-Goubalan AY, Saïdou A, Chrysostome CAAM, Kenis M, Amadji GL, Igué AM, Mensah GA. 2019. Physical and chemical properties of the agro-processing by-products decomposed by larvae of *Musca domestica* and *Hermetia illucens*. Waste Biomass Valoriz. https://doi.org/10.1007/s12649-019-00587-z

Bloukounon-Goubalan AY, Saïdou A, Clottey V, Chrysostome CAAM, Kenis M, Mensah GA. 2017. Typology of organic residues attracting flies and their utilization in agricultural sector in southern Benin. Int J Biol Chem Sci. 11 (6):2560–2572. doi:10.4314/ijbcs.v11i6.1.

Brewer LJ, Sullivan DM. 2003. Maturity and stability evaluation of composted yard trimmings. Compost Sci Util. 11 (2):96–112. doi:10.1080/1065657X.2003.10702117.

Cambardella CA, Richard TL, Russell A. 2003. Compost mineralization in soil as a function of composting process conditions. Eur J Soil Biol. 39:117–127. doi:10.1016/S1164-5563(03)00027-X.

Čičková H, Newton LG, Lacy CR, Kozánek M. 2015. The use of fly larvae for organic waste treatment. Review Waste Manage. 35:68–80. doi:10.1016/j.wasman.2014.09.026.

Cattanio JH, Kuehne R, Vlek PLG. 2008. Organic material decomposition and nutrient dynamics in a mulch system enriched with leguminous trees in the Amazon. Rev Bras Ciênc Solo. 32:1073–1086. doi:10.1590/S0100-06832008000300016.

De Neve S, Sleutel S, Hofman G. 2003. Carbon mineralization from composts and food industry wastes added to soil. Nutr Cycl Agroecosys. 67:13–20. doi:10.1023/A:1025113425069.

Dhanya B, Viswanath S, Purushothaman S. 2013. Decomposition and nutrient release dynamics of *Ficus benghalensis* L. Litter in traditional agroforestry systems of Karnataka, Southern India. Int Sch Res Notices. 2013:7 p.

Diener S, Studt Solano NM, Roa Gutiérrez F, Zurbrügg C, Tockner K. 2011. Biological treatment of municipal organic waste using black soldier fly larvae. Waste Biomass Valoriz. 2:357–363. doi:10.1007/s12649-011-9079-1.

FAO (Food and Agriculture Organization of the United Nations). 2006. World Reference Base for soil resources. [Accessed 2017 Dec 18]. www.fao.org.

Griffin TS, Hutchinson M. 2013. Compost maturity effects on nitrogen and carbon mineralization and plant growth. Compost Sci Util. 15(4):228–236. doi:10.1080/1065657X.2007.10702338.

Guntiñas ME, Leirós MC, Trasar-Cepeda C, Gil-Sotres F. 2012. Effect of moisture and temperature on net soil nitrogen mineralization: A laboratory study. Eur J Soil Biol. 48:73–80. doi:10.1016/j.ejsobi.2011.07.015.

Henin S, Dupuis M. 1945. Essai de bilan de la matière organique du sol. Ann Agron. 15:17–29.

Huang GF, Wong JWC, Wu QT, Nagar BB. 2004. Effect of C/N on composting of pig manure with sawdust. Waste Manag. 24:805–813. doi:10.1016/j.wasman.2004.03.011.

Kenis M, Bouwassi B, Boafo H, Devic E, Han R, Koko G, Koné N, Maciel-Vergara G, Nacambo S, Pomalegni SCB, et al. 2018. Small-scale fly larvae production for animal feed. In: Halloran A, Flore R, Vantomme P, Roos N. (Eds.). Edible insects in sustainable food systems. doi:10.1007/978-3-319-74011-9_15.

Kenis M, Koné N, Chrysostome CAAM, Devic E, Koko GKD, Clottey VA, Nacambo S, Mensah GA. 2014. Insects used for animal feed in West Africa. Entomol. 2:107–114.

Lupwayi NZ, Clayton GW, Donovan JTO, Harker KN, Turkington TK, Soon YK. 2006. Potassium release during decomposition of crop residues under conventional and zero tillage. Can J Soil Sci. 86:473–481. doi:10.4141/S05-049.

Masunga RH, Uzokwe VN, Mlay PD, Odeh I, Singh A, Buchan D, De Neve S. 2016. Nitrogen mineralization dynamics of different valuable organic amendments commonly used in agriculture. Appl Soil Ecol. 101:185–193. doi:10.1016/j.apsoil.2016.01.006.

Myers HM, Tomberlin JK, Lambert BD, Kattes D. 2008. Development of black soldier fly (Diptera: stratiomyidae) larvae fed dairy manure. Environ Entomol. 37(1):11–15. doi:10.1093/ee/37.1.11.

N'Dayegamiye A, Royer R, Audesse P. 1997. Nitrogen mineralization and availability in manure composts from Québec biological farms. Can J Soil Sci. 345–350. doi:10.4141/S96-004.

Njunie MN, Wagger MG, Luna-Orea P. 2004. Residue decomposition and nutrient release dynamics from two tropical forage legumes in a Kenyan environment. Agron J. 96:1073–1081. doi:10.2134/agronj2004.1073.

Olson JS. 1963. Energy storage and the balance of producers and decomposers in ecological systems. Ecol. 44:322–331. doi:10.2307/1932179.

Palm CA, Gachengo CN, Delve RJ, Cadisch G, Giller KE. 2001. Organic inputs for soil fertility management in tropical agroecosystems: application of an organic resource database. Agric Ecosyst Environ. 83:27–42. doi:10.1016/S0167-8809(00)00267-X.

Pastor B, Velasquez Y, Gobbi P, Rojo S. 2015. Conversion of organic wastes into fly larval biomass: bottlenecks and challenges. J Insects Food. 1:179–193. doi:10.3920/JIFF2014.0024.

Pitta CSR, Adami PF, Pelissari A, Assmann TS, Franchin MF, Luís César Cassol LC, Sartor LR. 2012. Year-round poultry litter decomposition and N, P, K and Ca release. Rev Bras Ciênc Solo. 36:1043–1053. doi:10.1590/S0100-06832012000300034.

Pomalégni SCB, Gbemavo DSJC, Kpadé CP, Kenis M, Mensah GA. 2017. Traditional use of fly larvae by small poultry farmers in Benin. J Insects Food. 3:187–192. doi:10.3920/JIFF2016.0061.

Rezig FAM, Elhadi EA, Abdalla MR. 2014. Decomposition and nutrient release pattern of wheat (*Triticum aestivum*) residues under different treatments in desert field conditions of Sudan. Int J Recycl Org Waste Agric. 3:69. doi:10.1007/s40093-014-0069-8.

Rose DJ, Inglett GE, Liu SX. 2010. Utilisation of corn (*Zea mays*) bran and corn fiber in the production of food components. J Sci Food Agric. 90:915–924.

Rovira P, Rovira R. 2010. Fitting litter decomposition datasets to mathematical curves: towards a generalised exponential approach. Geoderma, 155:329–343. doi:10.1016/j.geoderma.2009.11.033.

Rovira P, Vallejo VR. 2000. Examination of thermal and acid hydrolysis procedures in characterization of soil organic matter. Commun Soil Sci Plant Anal. 31:81–100. doi:10.1080/00103620009370422.

Saïdou A, Balogoun I, Ahoton EL, Igué AM, Youl S, Ezui G. 2017. Fertilizer recommendations for corn production in the South Sudan and Sudano-Guinean zones of Benin. Nutr Cycl Agroecosys. 110:361–373. doi:10.1007/s10705-017-9902-6.

Saïdou A, Bokossa HKJ, Fiogbé ED, Kossou D. 2016. Kinetic of pigs' manures decomposition and nutrient release pattern in ferralitic soil of Benin (West Africa). J Soil Sci Environ Manage. 7(6):73–80.

Semwal RL, Maikhuri RK, Rao KS, Sen KK, Saxena KG. 2003. Leaf litter decomposition and nutrient release patterns of six multipurpose tree species of central Himalaya, India. Biomass Bioenergy. 24:1428–1436. doi:10.1016/S0961-9534(02)00087-9.

Silver WL, Miya RK. 2001. Global patterns in root decomposition: comparisons of climate and litter quality effects. Oecologia. 129:407–419. doi:10.1007/s004420100740.

Spiess A, Neumeyer N. 2010. An evaluation of R^2 as an inadequate measure for nonlinear models in pharmacological and biochemical research: a Monte Carlo approach. Biomed Cent Pharmacolo. 10:6.

Thonnissen C, Midmore DJ, Ladka JK, Olk DC, Schmidhalter U. 2000. Legume decomposition and nitrogen release when applied as green manure to tropical vegetable production system. Agron J. 92:253–260. doi:10.2134/agronj2000.922253x.

Wang H, Wang S, Li H, Wang B, Zhou Q, Zhang X, Li J, 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.

Wang WJ, Baldock JA, Dalal RC, Moody PW. 2004. Decomposition dynamics of plant materials in relation to nitrogen availability and biochemistry determined by NMR and wet-chemical analysis. Soil Biol Biochem. 36:2045–2058. doi:10.1016/j.soilbio.2004.05.023.

Yang HS 1996. Modelling organic matter mineralization and exploring options for organic matter management in arable Farming in Northern China [PhD Thesis]. Wageningen. 164 p.