FERTILIZING POTENTIAL OF BIOGAS SLURRIES FROM FOOD WASTES AND EFFECTS ON NEMATODE POPULATIONS AND ENZYMATIC ACTIVITIES IN CULTIVATED SANDY SOILS

SALL, S. N.[1*] – NDIAYE, M. F.[2] – DJIGAL, D.[3] – NDIAYE, O.[1] – DIENG, D.[4] – DIOUF, D.[5]

[1]*Université Gaston Berger, Laboratoire des Sciences Biologiques, Agronomiques, Alimentaires et de Modélisation des Systèmes Complexes (LABAAM), BP 234, Saint-Louis, Sénégal*
(e-mail: saidou-nourou.sall@ugb.edu.sn; phone: +221 33 961 57 09 /33 961 17 68;
fax: 33 961 18 84)

[2]*Institut Sénégalais de Recherches Agricoles (ISRA) / Laboratoire National de Recherches sur les Productions Végétales (LNRPV). BP 3120 Dakar, Sénégal*
(e-mail: farmamame@yahoo.fr; phone: +221 77 324 71 06)

[3]*Institut Sénégalais de Recherches Agricoles (ISRA) / Centre pour le Développement de l'Horticulture (CDH). BP 3120 Dakar, Sénégal*
(e-mail: djigald@yahoo.com; phone: +221 77 324 71 06)

[4]*Université Gaston Berger, Département de Géographie, BP 234, Saint-Louis, Sénégal*
(e-mail: dah.dieng@ugb.edu.sn; phone: +221 77 611 36 65)

[5]*Université Gaston Berger, Département de Physique, énergies renouvelables, BP 234, Saint-Louis, Sénégal*
(e-mail: djicknoum.diouf@ugb.edu.sn; phone: +221 77 102 65 19)

[*]*Corresponding author*
e-mail: saidou-nourou.sall@ugb.edu.sn; phone: +221 77 562 07 07; fax: 33 961 18 84

(Received 18th Dec 2024; accepted 27th Feb 2025)

Abstract. This study evaluated the fertilizing potential of different slurries from methanization of food waste and their effect on soil microorganisms involving nematofauna and enzymatic activities. The experiment was performed in a shade house using six treatments consisted of three slurries produced by the biodigestions of potato peels (SP), food leftovers (SF), and mixture of potato peels and food leftovers (SMFP); traditional fertilizing manure (Man); farmer practice using mineral fertilizer (MF); and control (Ctrl, no amendments). Nematode abundance, trophic groups, nematodes ecological indices, and hydrolysis of fluorescein diacetate (FDA) were measured in rizosphere samples collected from corn after harvest. The SF and SMFP slurries increased the growth of corn to the same degree as mineral fertilizer (MF). The biogas slurries—which consist mainly of easily degradable materials—induce a significant increase in nematode abundance and hydrolysis of FDA. The SMFP gives the greatest increase in nematode populations, primarily bacterivores. SP and Man slurries, which are rich in phenol, cellulose, and lignin, increase the abundance of fungivores and decrease the growth of the corn. The slurries, particularly SMFP, increase the abundance of omnivorous nematodes while limiting the growth of the plant-parasitic nematodes. This work suggests a better management of organic waste for providing nutrients and regulating soil nematofauna.

Keywords: *digestate, biochemical quality, soil food web, soil cultivation, Senegal river valley*

Introduction

Senegal, like most developing countries, is experiencing a recurrent energy crisis due to its population growth and strong dependence on mostly imported fossil fuels (Dia et al., 2009). A significant portion of energy consumption should be derived from

DOI: http://dx.doi.org/10.15666/aeer/2303_45414562

renewable sources, such as biogas, which is produced via anaerobic decomposition of organic matter by microorganisms (Moletta, 2008). Biogas generated from organic waste materials, such as animal manure, cow dung, whole-plant silage, and food waste from humans and animals, is converted into electrical or thermal energy (Tambone et al., 2010). Moreover, biogas production technology offers an effective solution for utilizing organic waste in agricultural production. This technology generates digestate, a mixture of solid and liquid fractions, which has been widely shown to be rich in nutrients, making it valuable as a plant fertilizer and soil amendment (Tampio et al., 2016; Jamison et al., 2021). After filtration, drying, or composting, the solid fraction, or slurry, can be widely utilized as a biofertilizer for various crops (Möller and Müller, 2012; Drosg et al., 2015; Panuccio et al., 2019).

The physicochemical quality of the slurry depends strongly on the anaerobic digester technique and the quality of the wastes and effluents used in the anaerobic process (Khanal, 2008; Muscolo et al., 2017). Numerous studies in both the energy and agricultural sectors have explored the potential for biogas production using various organic materials, including agricultural residues, poultry waste, energy crops, municipal waste, cattle manure, and fruit and vegetable byproducts (Sormana, 1992; Diagne et al., 2016; Koninger et al., 2021). Feedstock availability, methane yield, microbial degradability or process stability of a feedstock and financial incentives are factors deciding which feedstock is favoured in the biogas sector. In Senegal, few studies have investigated the fertilizer potential of slurries from slaughterhouse waste and cattle manure (Ndiaye, 2014; PNB, 2016). These researches have demonstrated that digestate has excellent potential as a fertilizer, with equal or higher crop yields when using digestate animal manure compared to synthetic fertilizers or untreated manures. However, manure quantity and quality may vary seasonally based on livestock feeding and housing conditions. In addition, manure may contain pathogens, parasites, or heavy metals, posing health and environmental risks if not properly treated (Kumar et al., 2013; Kovačić et al., 2022; Chojnacka and Moustakas, 2024). and would have a negative impact on crop growth (Meng et al., 2019), on soil microbial diversity (Qi et al., 2022) and could be transferred to the fruit (Li et al., 2024a; Wang et al., 2024). Recently, Seck (2019) showed that the opportunities for recycling organic wastes are real in biogas digesters. The potentiality of the food wastes to produce biogas is high compared to other biodegradable substances used in anaerobic digester (Curry and Pillay, 2012; Kuo and Dow, 2017). This approach offers multiple advantages, including reducing landfill waste, cutting greenhouse gas emissions, and generating renewable energy.

University cafeterias in Senegal are a significant and highly diversified source of organic waste from mass catering. Most of this waste is either incinerated or sent to landfills. However, both uncontrolled incineration and untreated organic waste in landfills can generate methane, a potent greenhouse gas (Moletta, 1993). Reusing this organic waste should be a priority for the future to reduce its environmental impact and, in particular, to enhance the economic benefits for the university's agricultural farm and the surrounding small farmers. However, questions remain about the agronomic potential of slurries derived from food waste, especially their effects on soil biota and, consequently, soil health (van Midden et al., 2023). These changes in soil biological properties may have both positive and negative effects on crops (Wentzel and Joergensen, 2016; Jamison et al., 2021). The effects of slurries on biological functioning in sandy soils remain unknown. Studying soil nematofauna may help fill this knowledge gap. Numerous studies have explored the potential of digestate to suppress plant-parasitic nematodes (PPNs), which significantly harm essential crops. Laboratory experiments have shown a reduction in root-knot nematode populations in soils treated with digestate compared to those without digestate application (Westphal et al., 2016; Das et al., 2021). The mechanisms by which organic amendments suppress PPNs remain speculative. It has been suggested that PPN control occurs through the stimulation of naturally occurring antagonists and alterations in the soil nematode community structure (Min et al., 2011; Dieng et al., 2023). However, research on the nematicidal potential of digestate is limited (Das et al., 2021). Therefore, studying the effects of food waste slurry on specific ecological groups of nematodes is essential.

Nematodes differ in their sensitivities and responses to the application of organic amendments (Djigal et al., 2012; Chauvin et al., 2015; Sall et al., 2020; Dieng et al., 2023). They are considered indicators of agricultural practices as well as the structure and functioning of soil trophic networks (Porazinska et al., 1999; Villenave et al., 2010). Microorganisms play a key role in organic matter decomposition through the detrital food chain, interacting with soil mesofauna (Bardgett and van Der Putten, 2014), including nematodes. Nematodes belong to microfaunal groups that influence microbial activity and are recognized as important regulators of nutrient release processes (Griffiths, 1994). Information about microbial activity is therefore crucial in the sandy soils of the Senegal River Valley, where soil fertility is essential for improving productivity. Enzyme activities are reliable indicators of soil fertility (Karaca et al., 2011).

In this study, we used three biogas slurries and the solid fraction of digestates, previously separated from their liquid fraction (Ndong and Labou, 2019), obtained through the methanization of food waste from university cafeterias. The specific objectives of our study were to: (1) analyze the biochemical composition of the slurries and evaluate their effects on maize (*Zea mays*) growth, and (2) determine their impact on the associated soil microbial communities, including nematofauna and enzymatic activities.

Review of literature

The slurry produced after biogas production, known as anaerobic digestate, contains residual organic matter and can be used as a fertilizer, soil conditioner and biopesticide in agriculture. Digestate has demonstrated excellent fertilizer potential, with several studies reporting comparable or even higher crop yields when using digestate compared to synthetic fertilizers or undigested animal manures (Nkoa, 2014; Ehmann et al., 2018; Barzee et al., 2019). It contained a range of nutrients readily absorbed by crops, including nitrogen, phosphorus, potassium, and trace minerals such as calcium, copper, iron, zinc, and manganese (Feng et al., 2011). Studies have shown that digestates produced from organic materials, such as animal slurry, contain higher levels of mineral nitrogen than their non-digested counterparts (Baral et al., 2017; Kumar et al., 2022). Digestate is a heterogeneous substance in terms of its chemical composition and is influenced by the feedstock and operational conditions of the anaerobic digester. It might be expected that the differences in composition affect fertiliser value, as well as built up of soil organic matter (SOM). A significant proportion of SOM consists of living and dead microorganisms (Liang and Balser, 2011). Soil microorganisms consist of archaea, bacteria, fungi, and protozoa, though the majority of studies investigating the impact of digestate on soil microorganisms have focused on bacteria and fungi as dominant groups in terms of abundance and biomass. The focus on these two microbial groups is largely because they are considered the largest functional groups responsible for nutrient cycling in soil (van Midden, 2023). The application of digestates to soils rapidly stimulates microbial activity (Risberg et al., 2017; Meng et al., 2022). Alburquerque et al. (2012) and Risberg et al. (2017) both reported significant differences in the effects of digestate on microbial activity due to the digestate feedstock type. Digestates containing a greater amount of readily available carbon resulted in increased levels of soil enzyme activities (Makádi et al., 2007). Phenolic compounds, polycyclic aromatic hydrocarbons and other substances contained also in anaerobic fermentation byproducts negatively affected soil enzyme activity (Chen et al., 2012).

Very few studies have looked at how anaerobic digestate impacts soil meso-organisms, particularly nematodes (van Midden et al., 2023). Numerous studies have explored the use of digestate for suppressing plant-parasitic nematodes (PPNs), which are known to cause significant damage to essential crops. Attributing the effects of digestate applications to changes in whole ecological groups of nematodes is challenging due to the limited number of studies conducted on this topic (Westphal et al., 2016; Wang, 2019) and their large diversity, which include both free-living nematodes (FLNs) and plant-parasitic nematodes. The majority of soil nematodes are the FLNs, which are important beneficial to soil health and to plant growth (Djigal et al., 2012). They play a vital role in carbon and nutrient cycling. Several studies have reported that changes in FLN communities can depend on the decomposition pathways or biochemical quality of organic matter added to soil (Chauvin et al., 2015; Bongiorno et al., 2019). Various nematode ecology indices, which are calculated based on the classification of nematodes into functional guilds, are efficient tools for assessing soil fertility, degradation pathways, and food web structure and function (Bongers and Ferris, 1999; Ferris, 2010). A few studies have demonstrated that nematode communities can reflect changes in the soil environment after biogas slurry application (Mahran et al., 2009; Li et al., 2024b). Mahran et al. (2009) found that the bacterial pathway was dominant as biogas slurry was added to soil.

Some studies have suggested that organic residues increase microbial activity, such as enzyme activity, enhance trophic interactions within the soil food web, and promote the abundance of higher trophic groups (Sánchez-Moreno et al., 2009; Chauvin et al., 2015; Sall et al., 2020). These changes may, in turn, facilitate the regulation of plant-parasitic nematodes (PPNs) through predation by antagonistic microflora (Oka, 2010; Ferris et al., 2012). The microbial responses and the ecological succession of nematodes are influenced by the characteristics of the organic residues applied (Oka, 2010; Chauvin, 2015; Dieng et al., 2023). However, this relation is not clearly defined when digestates are used particularly in Senegal River Valley’s sandy soil. Sandy soils are well known to have very little resilience and to be very sensitive to agro-climatic stress. Free-living nematodes thrive in well-aerated conditions, whereas plant-parasitic nematodes may struggle in dry environments (Bongers and Ferry, 1999; van den Hoogen et al., 2019). These soils are also typically low in organic matter and nutrients (Blanchart et al., 2007) which can limit microbial populations and indirectly affect nematodes that feed on bacteria and fungi.

Materials and methods

This study was conducted on the agricultural farm of Senegal’s *Université Gaston Berger (UGB) de Saint-Louis*, located in Sanar (16°03’N, 16°25’W), in the Department of Saint-Louis. Methanization was carried out in an artisanal batch-type digester, which had been assembled in one of the university’s laboratories (*Fig. 1*). The resulting digestate was filtered to separate the solid and liquid phases. The solid phase was dried in the shade for a week, then stored in cold storage until analysis and use. The liquid phase was not used.

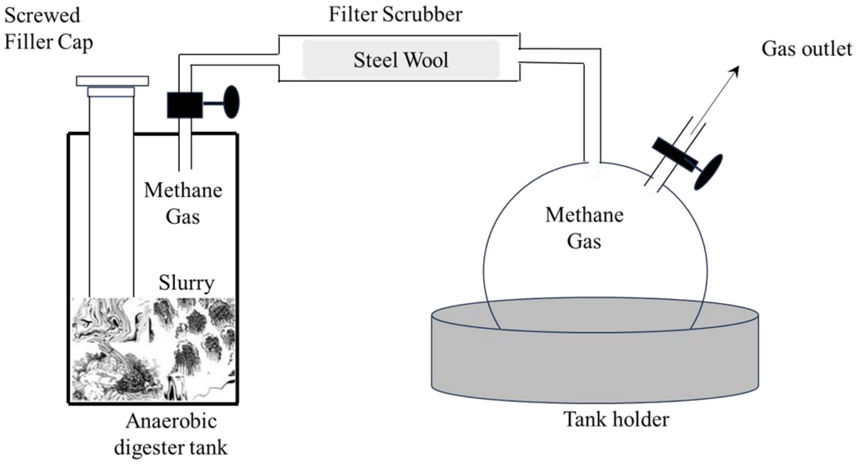

Figure 1. *Schematic graph of the artisanal batch-type digestor*

Biological materials

Slurries from three types of food waste were used: potato peels (SP), food leftovers (SF), and a mixture of food leftovers and potato peels (SMFP). The composition of the biogas produced during the methanization of these materials was as follows: SP (35–40%), SF (7–8%), and SMFP (49–51%), according to Ndong and Labou (2019). A fourth slurry was produced classically from cow manure.

Maize (*Zea mays*) was used as a test plant to evaluate the effects of the different slurries on growth and production. It serves as a model crop for studying soil fertility and the effects of various fertilizers (organic and inorganic) on the university farm. Maize is widely used due to its economic importance, adaptability, and biological characteristics. The seeds used in this study were harvested from the university farm.

Biochemical characterization of the organic wastes

Contents of polyphenols and humic compounds were determined at the UGB’s Laboratory of LABAAM (*Laboratoire des Sciences Biologiques, Agronomiques, Alimentaires et de Modélisation des Systèmes Complexes*). All other biochemical and physicochemical analyses were done at LNRERV-ISRA (*Laboratoire National de l’Elevage et de Recherches Vétérinaires*).

Biochemical compounds of the organic residues were determined by the method of Van Soest (1991): Hemicellulose, cellulose and lignin were analysed as acid detergent fibre (ADF) and acid detergent lignin (ADL).

The potential quantity of stable humus was estimated according to Robin (1997). The relation between the C content that remains in a soil after amendment (Tr), and the different organic fractions and inorganic fraction (Ash) in the amendment, is given by the *Equation 1*:

$$\begin{gathered} TR = (0.3221 * SOL) - (0.7155 * HEM) + (0.6717 * CEL) + \\ (1.8919 * LIG) + (0.0271 * Ash) \end{gathered} \tag{Eq.1}$$

where Tr is expressed as a percentage of the carbon content of the amendment's dry matter, and SOL, HEM, CEL, LIG and Ash are expressed in percentages of dry matter. For example, a Tr of 30 means that 30% of the C that was present in the amendment was stabilized (humified) after application, and 70% was lost as CO_2 due to soil mineralisation (Robin, 1997).

Total phenol content was extracted according to the method described by Li et al. (2006) and quantified using the Folin-Ciocalteu method, as reported by Boizot and Charpentier (2006). Gallic acid was used as a standard for analysis. Total phenol content is expressed in mg equivalent of gallic acid per gram of dry weight (mg Eq GA/g d.w.).

Experimental design

A completely randomized block design (application of six fertilising treatments to maize, with three repetitions) was implemented in the greenhouse of the University's agricultural farm. For each treatment (and for each of its replications), a separate 10-L bucket was filled 2/3 full with dampened soil (approximately 15 kg). The soil used, was a composite sample taken from the 0-20 horizon in a plot that had been left fallow for five years after producing a crop of pepper (*Capsicum annum*). Organic C and N content, total P, assimilable P, CEC, clay, silt and sand contents were, respectively, 1.83 g C kg^{-1} dw soil, 0.16 g N kg^{-1} dw soil, 34.9 mg kg^{-1} dw soil, 4.88 mg kg^{-1} dw soil, 1.4 meq %, 3.3%, 3% and 93,5% (Sall et al., 2020).

Fertilisation was the only factor that was studied. One of the treatments (Ctrl) was an absolute control (no amendments). A second treatment (MF) was a positive control consisting of the local farmers' practice of applying type 9-23-30 NPK mineral fertilizer at 200 kg/ha. The third treatment (Man) was traditional fertilization with 10 t/ha of cow manure. The remaining three treatments were biogas slurries from (a) the digestion of potato peels (SP), (b) food leftovers (SF), and (c) a mixture of food leftovers and potato peels (SMFP). All residues were applied at a rate equivalent to 10 t/ha. This corresponds to supply sufficient rate that would produce maximum soil benefits from the added organic matter in west Africa cropland (Bationo et al., 2007).

The residues and fertilizers were mixed into the soils of the respective buckets one week before planting the maize crop (*Zea Mays*).

During the experiment, the buckets were irrigated every two days with 250 mL of water per plant. Three months and ten days after planting, the plants were removed from the buckets. The roots and above-ground parts were separated, oven-dried at 70°C for 72 hours, and weighed to determine leaf and root biomass.

Visual examination revealed no root galls indicative of infestation by *Meloidogyne nematodes*. Soil from each bucket was sampled using a transplanter from the root zone (0–20 cm depth) and placed in bags for nematode extraction and vials for enzyme activity measurement.

Analyses

Abundance and trophic structure of the nematodes

Nematodes were extracted from soil via the Seinhorst elutriator method (1962). Briefly, a 250 g sample of soil (fresh weight) from each bucket was subjected to the method's three phases: elutriation, sifting, and active passage (in which nematodes were separated from soil based on their mobility). The total nematodes were counted under a 40x binocular magnifier (Leica, Leica microsystems, Wetzlar-Germany*)*. The nematodes were then fixed with 60 °C formaldehyde (4%; pH 7) under a fume hood. About 150 nematodes were identified by examining mass slides under a 400x optical microscope (Leica, Leica microsystems, Wetzlar-Germany) to genus or family level and then assigned to the five trophic groups following Yeates et al. (1993): bacterivores (Ba), fungivores (Fu), omnivores (Om), carnivores (Cr), and plant-parasitic nematodes (PPN). The results were expressed as (number of nematodes)/ (kg of dry soil).

Ecological indices

To assess food web characteristics, the Shannon Index (H'), Nematode Channel Ratio (NCR), Enrichment Index (EI), and Structure Index (SI) were calculated following the method of Ferris et al. (2001). These indices are derived independently based on the weighted abundance of nematode guilds. Nematode guilds comprise bacterivores (Bax), fungivores (Fux), predators (Prx), and omnivores (Omx) ranging along the c-p scale from x = 1 to x = 5. Nematodes of c-p 1 have a short life cycle, high fecundity, are tolerant to disturbance, and can be ascribed to r-strategists. In contrast, nematodes of c-p 5 produce few large eggs, have a long-life cycle combined with a long generation time, and are sensitive to disturbance resembling K-strategists. Values ranging from 1 to 5 represent varying degrees between these contrasting life history strategies (Neher and Darby, 2009). Plant feeders are excluded from this system because their response to nutrient addition differs (Bongers and Ferris, 1999). The relative abundance of these guilds indicates specific soil conditions and food web characteristics, including enrichment levels, disturbance, and complexity.

Shannon index (H')

$$H' = -\sum_{i=1}^{s} pi * \log(pi), \qquad \text{(Eq.2)}$$

with i: a given taxon; pi: taxon i's proportional abundance (= ni/N); ni: number of individuals of the taxon i in the sample; N: the total number total of individuals for all the taxa of nematodes in the sample.

Nematode Channel Ration (NCR)

$$\mathrm{NCR} = \frac{B}{B+F} \qquad \text{(Eq.3)}$$

where,
B= Abundance of bacterivore nematodes,
F= Abundance of fungivore nematodes.

Enrichment Index (EI)

$$\mathrm{EI} = 100 * \left(\frac{e}{e + b}\right) \qquad \text{(Eq.4)}$$

where,
e = the weighted abundance of individuals in the guilds Ba1 and Fu2 (respectively, the bacterivores of class c-p 1 and the fungivores of class c-p 2). e represents components of the nematofauna that are indicative of resource enrichment;
b = the weighted abundance of individuals in the guilds Ba2 et Fu2 (bacterivores of class c-p 2 and fungivores of class c-p 2, respectively). b represents components of the nematofauna that are indicative of basal food web functioning.

Structure Index (SI)

$$\mathrm{SI} = 100 * \left(\frac{s}{s + b}\right) \qquad \text{(Eq.5)}$$

where,
s = the weighted abundance of individuals belonging to guilds Ba3, Ba4, Ba5 (respectively, bacterivores of classes c-p 3, 4, and 5); Fu3, Fu4, and Fu5 (respectively, fungivores of classes c-p 3, 4, and 5); Ca3, Ca4, and Ca5 (predators c-p 3, 4, and 5, respectively); and Om4 and Om5 (omnivores of classes c-p 4 and 5, respectively). These guilds of nematodes represent a ‘structured’ trophic network;
b = the weighted abundance of individuals in the guilds Ba2 and Fu2 (respectively, bacterivores of classes c-p 2 and fungivores of class c-p 2).

Measurement of enzymatic activities

The hydrolysis of fluorescein di-acetate (FDA) was measured according to the method of Adam and Duncan (2001). Briefly, 1 g of fresh soil was incubated at 30 °C for one hour in 15 ml of universal buffer that had been modified to pH 7.6, and to which 200 µl of FDA substrate had been added. The reaction was then stopped by adding 1 ml of acetone, after which the optical abundance at 490 nm was measured via spectrophotometry. The hydrolysis of FDA was expressed in µg fluorescein g^{-1} soil h^{-1}.

Statistical analysis

Analyses of variance (ANOVA) were performed using R (version 4.0.2, R Foundation for Statistical Computing, Vienna, Austria). A p-value of <0.05 was considered statistically significant by using Tukey’s test for comparison of means. A logarithmic transformation was performed with data that did not follow a normal distribution and/or respect for homoscedasticity. The same software was used for a Principal-Component Analysis (PCA) of the enzymatic activities and trophic groups.

Results

Biochemical qualities of the slurries

The biochemical compositions of the slurries differed according their nature (*Table 1*). All of the slurries had higher soluble fractions (> 60% dry weight) compared to the manure (43.8% dry weight). However, the manure had higher Ash (25.49%) and cellulose (17.63%) contents than slurries (respectively 3.31 and 4.74%). SP slurry had the highest lignin content (17.07%) and humus potential (Tr = 50.7% of C). Manure had the second-highest value (Tr = 31.41% of C). Table 1 showed that the total polyphenol content was higher in the SP slurry (0.46 mg Eq GA/g d.w.), followed by manure (0.32 mg Eq GA/g d.w.). Phenol contents were the same in the SMFP and SF slurries (0.17 mg Eq GA/g d.w.).

Table 1. *Biochemical compositions of the slurries from methanization of the initial materials*

	Ash	**SOLU**	**HEMI**	**CELL**	**LIGN**	**Tr**	**Phenols**
			% of dry matter			% of C	mg eq GA / g dry matter
SP*	9.85	63.44	6.33	3.31	17.07	50.70	0.46
SF	5.36	63.37	22.22	4.49	4.56	16.30	0.17
SMFP	3.13	62.02	26.57	4.74	3.55	10.94	0.17
Man	25.49	43.86	7.62	17.63	5.39	31.41	0.32

*SP: slurry from potato peels; SF: slurry from food leftovers; SMFP: slurry from mixture of food leftovers and potato peels; Man: slurry from cow manure; Ash: inorganic part of each material; SOLU: soluble fraction; HEMI: hemicellulose fraction; CELL: cellulose fraction; LIGN: lignin fraction; Tr: stable-humus potential

Agro-morphological parameters

Plant lant heights (PH) did not differ significantly between amended soils, whereas the absolute control (Ctrl, = no fertilization) soil showed the lowest values (*Table 2*).

Table 2. *Mean agro-morphological parameters of maize plants (Zea mays) grown in soils that received the six treatments*

Treatments*	**PH** (cm)	**NL**	**LB** (g)	**RB** (g)
Ctrl	153.67 b	16 a	31.44 b	11.97 b
MF	251.47 a	16 a	69.84 a	24.51 a
SP	220.30 a	13 a	41.14 b	13.40 b
SF	237.75 a	15 a	62.86 a	27.38 a
SMFP	242.60 a	15 a	63.62 a	25.45 a
Man	226.90 a	15 a	45.12 b	12.35 b

***** Ctrl: Absolute control (no fertilization), MF: mineral-fertilized control, SP: slurry from potato peels, SF: slurry from food leftovers, SMFP: slurry from mixture of food leftovers and potato peels, Man: manure. PH=height at harvest, LB= leaves biomass, RB=root biomass; NL=number of leaves. Within a given column, values that are labelled with different letters are significantly different ($p < 0.05$)

LB and RB showed the same trend. MF, SF, and SMFP presented the highest values (69.84 g, 62.86 g, and 63.62 g for LB, and 24.51 g, 27.38 g, and 25.45 g for RB, respectively) but were not significantly different from each other. The Ctrl, SP, and Man treatments showed the lowest values and were also not significantly different from each other.

Nematode population abundances, trophic structures, taxonomic diversity, and ecological indices

For the six treatments, abundances of nematode varied from 3033 to 14620 individuals/kg of dry soil (*Fig. 2*). The abundance of nematodes between the treatments SP (9453 individuals/kg of dry soil), SF (11073 individuals/kg of dry soil), and SMFP (14260 individuals/kg of dry soil) were not significantly different. Total abundance in the Ctrl (3033 individuals/kg of dry soil) was significantly lower (p = 0.00149) compared to these three treatments. Abundance of nematodes for treatments MF and Man were not significantly different to the Ctrl (*Fig. 2*).

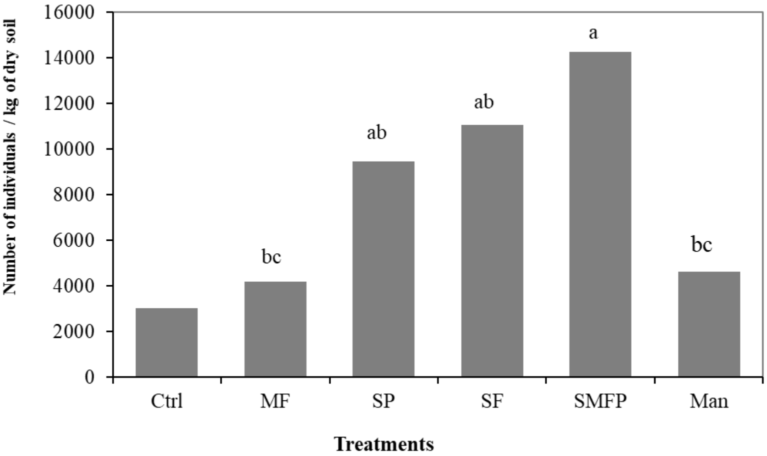

Figure 2. *Total abundance of nematodes for each treatment. Ctrl: Absolute control (no fertilization), MF: mineral-fertilized, SP: slurry from potato peels, SF: slurry from food leftovers, SMFP: slurry from mixture of food leftovers and potato peels, Man: manure. *Treatments whose bars are labelled with the same letter are not significantly different from each other according to ANOVA (p < 0.05, with Tukey's test)*

In all six treatments, predator nematodes were completely absent, and bacterivore nematodes dominated followed by omnivore nematodes (*Fig. 3*). Compared to other trophic groups, the abundance of bacterivores in the soils amended with slurries is remarkable. Treatment SMFP gave the highest bacterivore abundance (11294 individuals/ kg of dry soil), compared to the Ctrl (1525 individuals/ kg of dry soil). These organic treatments increased bacterivore abundances by 74%, 54%, and 42% respectively. Total abundance of bacterivores in SF and SP were respectively 8301 and 6538 individuals/ kg of dry soil (*Fig. 3*).

Abundances of plant parasitic nematodes were significantly higher in MF treatment (1460 individuals/ kg of dry soil) compared to SP and SMFP treatments. In contrast, omnivore abundance was significantly lower in the MF treatment and higher in the SP and SMFP treatments.

Abundances of fungivore nematodes were relatively low in all treatments. The highest abundance was in SP (213 individuals/ kg of dry soil).

Within the set of 18 soil samples, 33 taxa of nematodes belonging to 10 families, were identified (*Table 3*). The bacterivores were the most diverse with 16 taxa. The bacterivore taxon with the largest populations were *Acrobeloides* and *Chiloplacus*. The *Acrobeloides* taxon was significantly more abundant in soil amended with SP.

Omnivores were the second most diverse trophic group, with 8 taxa. The majority of the omnivorous nematodes belonged to the taxa *Eudorylaimus* and *Qudsianematidae*. Populations of *Eudorylaimus* were significantly highest in soils amended with slurries. Plant-parasitic nematodes were represented by the taxa *Pratylenchus*, *Paratylenchus*, *Tylenchidae*, *Helicotylenchus* and *Tylenchorhynchus*. It noteworthy that *Helicotylenchus* and *Tylenchorhynchus* were absent in soils that were amended with slurries.

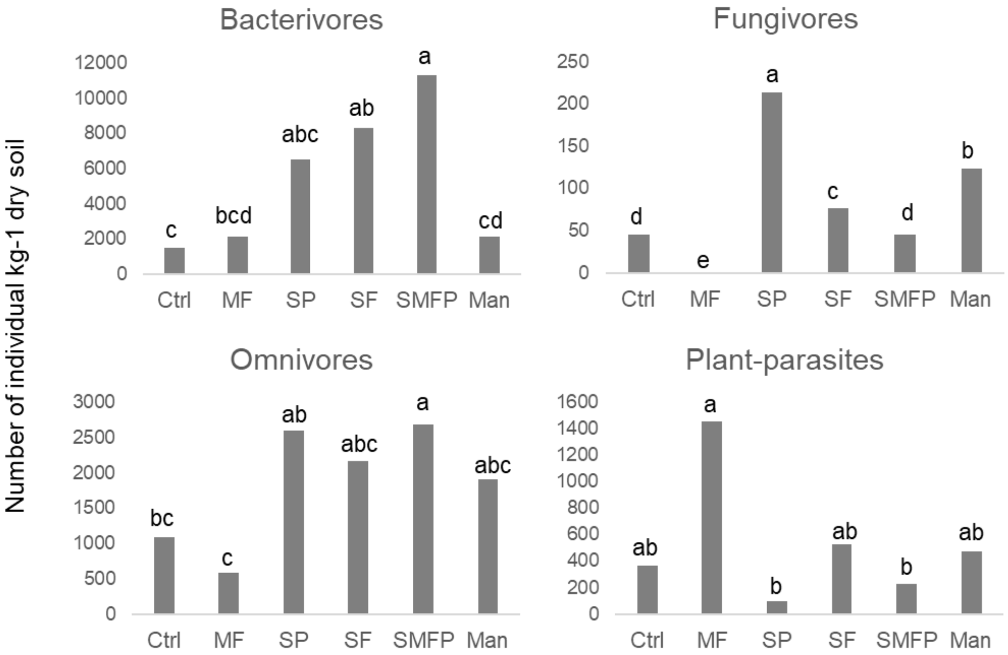

Figure 3. *Trophic structures of the nematode populations for each treatment. Ctrl: Absolute control (no fertilization), MF: mineral-fertilized, SP: slurry from potato peels, SF: slurry from food leftovers, SMFP: slurry from mixture of food leftovers and potato peels, Man: manure. * Treatments whose bars are labelled with the same letter are not significantly different from each other according to ANOVA ($p < 0.05$, with Tukey's test)*

Analyses of the ecological indices found no significant differences for the Shannon indices (H'), the nematode channel ratio (NCR), and the enrichment index (EI) of the six treatments. However, the differences between structural indices (SI) for SMFP (25.04), Man (9.23), and MF (15.64) were significant.

Activity of fluorescein diacetate (FDA)

Hydrolysis of FDA differed among the treatments (*Fig. 4*). All four organic amendments (SP, SF, and SMFP, and Man) increased the FDA. In particular, activities were significantly higher in the SMFP and Man amended soils (respectively, 20.93 and 20.81 µg fluorescein g-^{1} soil h-^{1}) than in the two controls (12.43 µg fluorescein g-^{1} soil h-^{1} for Ctrl, and 11.72 g-^{1} soil h-^{1}for MF). However, there was no significant difference between activities of manure- and slurry-fertilized soils.

Table 3. *Taxa, functional guilds, and ecological guilds of nematodes, for each treatment*

Functional guilds	**Taxa**	**Treatments**					
		Ctrl	**MF**	**SP**	**SF**	**SMFP**	**Man**
Ba1	*Macrolaimus*	0 e	78 ±67 c	128±175 a	99±171 b	0 e	53±91 d
	Mesorhabditus	15±26 d	0 e	218±378 a	163±282 a	97±106 c	0 e
	Panagrocephalus	0 b	20±35 a	19±33 a	0 b	0 b	0 b
Ba2	*Acrobeloides*	0 f	332 ±104 e	2113 ± 335 a	523 ±583 c	1415±773 b	350 ± 200 d
	Cephalobus	38±35 f	114±66 c	436±169 b	106±94 d	1308±124 a	84±37 e
	Heterocephalobus	0 f	73± 64 d	82±142 c	139±240 b	159±158 a	18± 30 e
	Cervidellus	15±26	20±35	56±98	0	0	0
	Metacrobeles	0	40±70	113±196	0	0	35±61
	Acrobeles	59±103 b	110±96 ab	413±362 ab	396±514 ab	1192±694 a	312±298 ab
	Chiloplacus	1137±175 ab	1161±228 ab	1268±467 ab	4957±3884 ab	5639±260 a	515±243 b
	Monhystera	0 b	0 b	27±47 a	0 b	0 b	0 b
	Stegelleta	0 d	0 d	0 d	377±653 a	198±173 b	18±30 c
	Alirhabditis	0 d	0 d	446±678 a	98±169 c	349±156 b	0 d
	Zeldia	224±219 a	174±165 a	1219±456 a	1364±659 a	937±409 a	677±559 a
Ba3	*Rhabdolaimus*	15±26 a	0 a	0 a	40±69 a	0 a	0 a
Ba4	*Bathyodontus*	23±39 c	40±70 b	0 d	40±69 b	0 d	49±53 a
Fu2	*Aphelenchus*	30±52 b	0 d	19±32 c	43±38 a	0 d	0 d
	Aphelenchoides	0 d	0 d	54±94 a	33±56 b	27±45 c	0 d
	Ditylenchus	15±26 b	0 c	0 c	0 c	0 c	123±110 a
Fu4	*Tylencholaimus*	0 c	0 c	140±176 a	0 c	19±32 b	0 c
H2	*Tylenchidae*	85±111 a	86±101 a	38±33 a	43±38 a	35±61 a	18±30 a
	Paratylenchus	53±91 a	20±35 a	0 a	24±41 a	0 a	0 a
H3	*Pratylenchus*	231±275 ab	1284± 831 a	56±98 b	459±456 ab	194±213 ab	445±163 ab
	Helicotylenchus	0 a	33±57 a	0 a	0 a	0 a	14±24 a
	Tylenchorhynchus	0 b	37±65 a	0 b	0 b	0 b	0 b
Om4	*Labronema*	30±52 b	20±35 c	0 d	0 d	62±55 a	0 d
	Qudsiadnematidae	895±148 a	370±69 a	2210±289 a	1614±372 a	2137±271 a	1501±185 a
	Eudorylaimus	1425±377 bc	724±277 c	3784±226 a	3792±440 a	3076±459 ab	2555±386 abc
	Dorylaimus	0 b	49±29 b	997±140 a	668±120 ab	644±88 ab	42±24 b

DOI: http://dx.doi.org/10.15666/aeer/2303_45414562

Functional guilds	**Taxa**	**Treatments**					
		Ctrl	**MF**	**SP**	**SF**	**SMFP**	**Man**
Om5	*Aporcelaimus*	271±60 b	0 f	82±47 d	71±41 e	322±105 a	158±91 c
	Aporcelaimellus	0 c	0 c	82±47 b	0 c	0 c	105±61 a
	Thonus	399±62 a	529±104 a	671±151 a	368± 155 a	1333±331 a	1389±298 a
	Ecumenicus	68±118 b	0 c	0 c	0 c	126±111 a	0 c
Ecological indices	*H'*	0.94 a	0.82 a	0.90 a	0.98 a	0.81 a	0.87 a
	NCR	0.98 a	0.94 a	0.97 a	0.99 a	0.99 a	0.95 a
	EI	0.58 a	1.44 a	0.03 a	2.18 a	0.21 a	0.73 a
	SI	23.85 ab	15.64 b	5.69 ab	58.01 ab	25.04 a	9.23 b

*Ctrl: Absolute control (no fertilization), MF: mineral-fertilized control, SP: slurry from potato peels, SF: slurry from food leftovers, SMFP: slurry from mixture of food leftovers and potato peels, Man: manure. H (Shannon Index), EI (Enrichment Index), SI (Structure Index), and CI (Channel Index). Ecological Index Ba = bacterial feeders, Fu = fungal feeders, Om = omnivorous, subscript numbers indicate the corresponding c-p classification. Subscript numbers refer to the related c-p-classification of nematodes (see text for details). Within a given line, values that are followed by the same letter are not significantly different from each other according to the ANOVA test, with Tukey's test, with $p < 0.5$

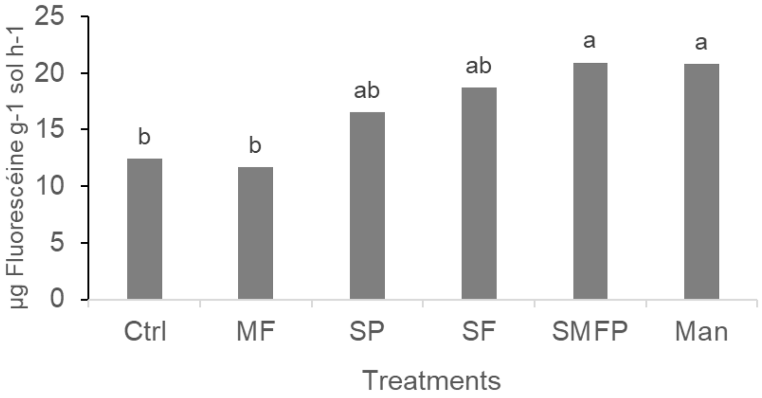

Figure 4. *Activity of fluorescein diacetate (FDA) for each treatment. Ctrl: Absolute control (no fertilization), MF: mineral-fertilized, SP: slurry from potato peels, SF: slurry from food leftovers, SMFP: slurry from mixture of food leftovers and potato peels, Man: manure. * Treatments whose bars are labelled with the same letter are not significantly different from each other according to ANOVA (p < 0.05, with Tukey's test)*

Relationships between agro-morphological parameters, trophic groups, and the FDA

The principal component analysis (PCA) of these results showed that 84.04% of the total information is extracted by the first two PCA dimensions (*Fig. 5*). Dimensions 1 and 2 explain, respectively, 46.0% and 37.95% of the variance. Dimension 1 is positively correlated with the variables Fungivores (r = 0.86), Omnivores (r = 0.90) and FDA (r = 0.63).

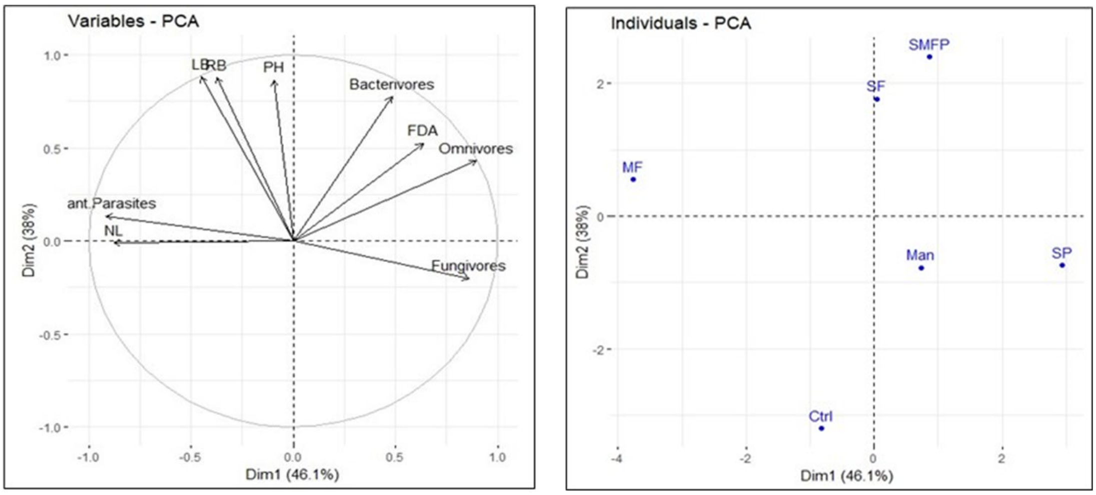

Figure 5. *Principal components analysis (PCA). 5A: circle of correlation among variables; 5B: distribution of treatments. Ctrl: Absolute control (no fertilization), MF: mineral-fertilized, SP: slurry from potato peels, SF: slurry from food leftovers, SMFP: slurry from mixture of food leftovers and potato peels, Man: manure. PH=height at harvest, LB= leaves biomass, RB=root biomass; NL=number of leaves*

In addition, dimension 1 is negatively correlated with the variables Plant Parasitic nematodes (r = - 0.92) and NL (r = - 0.88). The variables correlated positively with dimension 2 are Bacterivores (r = 0.78), LB (r = 0.88), RB (r = 0.88), and PH (r = 0.86).

These results indicate that MF treatment increased the NL, while the SF and SMFP slurries stimulated PH, as well as RB and LB. The treatments SF and SMFP resulted in high abundances of Bacterivore nematodes, which are much less abundant in the unfertilized (Ctrl) treatment. By contrast, the SP treatment led to a high abundance of Omnivore and Fungivore nematodes, and high FDA hydrolysis (*Fig. 5*). Plant-parasitic nematodes are lower in SP and higher in MF treatment.

Discussion

Effects of slurry on plant growth

SF, SMFP, and MF treatments produced the best results for maize growth. However, the differences in plant growth among these three treatments were not significant. These results, which are consistent with those obtained by Losak et al. (2011) and Sogn et al. (2018), can be explained by the partial mineralization of organic material during biomethanization, which makes essential nutrients available for plant growth.

Several contradictory studies have reported either a positive effect of digestates on root growth (Gunnarsson et al., 2010) or a negative effect (Andruschkewitsch et al., 2013).

Wentzel and Joergensen (2016) found no difference in root biomass when using digestate compared to mineral fertilizer. In fact, slurries contain high fractions of soluble material, which contribute to high FDA hydrolysis activity, releasing essential nutrients such as N, P, and K. Tan et al. (2021), using urease activity as an indicator, also observed an increase in enzymatic activity and the availability of these nutrients after digestate application. In this way, slurries stimulated plant growth, as well as root and leaf biomass accumulation. This is supported by the high content of readily available nutrients for plants (Möller and Müller, 2012). Additionally, Tambone and Adani (2017) showed that the nitrogen mineralization rate in digestate is very similar to that of mineral fertilizer (Urea).

However, treatments with SP and Man, which also had high fractions of soluble material, resulted in the lowest growth parameter values. This result could be explained by the high polyphenol content in SP and Man, which may partially complex nutritive substances, specifically ammonium nitrogen (NH_4^+-N), known to be abundant in digestates (Jamison et al., 2021). Indeed, polyphenol compounds can reduce the accessibility of soluble carbohydrates and proteins, thereby limiting nitrogen availability (Sall et al., 2003). This possibility is supported in our study by the highest stable humus potential (Tr) observed for SP and Man, indicating the presence of more complex molecular structures.

Effects of slurry on abundances and trophic structure of the nematodes

In this experiment, the nematodes in the control soil are present in an abundance relatively comparable to the global trends found in the literature (Villenave et al., 2010; Van den Hoogen et al., 2019). The abundances of nematodes are significantly increased by the three slurries (SP, SF, and SMFP). This result could be explained by their high organic matter (OM) content, which serves as a source of carbon and nutrients for nematodes. Li et al. (2011) note that food waste is an important source of fermentable OM. Therefore, slurries resulting from the methanization of food waste (such as those in this study) provide abundant organic carbon for nematodes, which are able to reproduce in any environment that supplies these substances (Bongers and Ferris, 1999; Tabarant et al., 2011). Abundances of nematodes were not significantly different between the three slurries that had substantially the same OM contents. In addition, all three slurries favoured the proliferation of bacterivore nematodes, to the detriment of fungivores. The presence of bacterivores appeared to be positively correlated with hydrolysis of FDA, which indicates a high level of bacterial activity in the soil. Therefore, the correlation noted here, which was also reported by Chauvin et al. (2015) and Djigal et al. (2012), suggests that the application of organic slurries induces a high bacterial activity along with an increase in bacterivore abundance.

This result was also confirmed by Mahran et al. (2009) who found that the bacterial pathway was dominant as biogas slurry was added to soil. Moreover, the structural nature of the OM affects the trophic makeup of the nematode populations. For example, fungivores were more abundant in soils amended with SP and Man. These two slurries have the highest stable-humus potentials (Tr) because they also have the highest contents of lignin, cellulose, and phenols. These biochemical compounds induce a high fungal activity (Sall et al., 2003) and therefore increase the fungivore populations (Chauvin et al., 2015; Sall et al., 2020).

At the same time, SP-amended soils induced smaller populations of plant-parasitic nematodes compared to the controls, both with and without mineral fertilization. This may be attributable to the high polyphenol content in SP, whose nematicidal effects on plant-parasitic nematodes have been demonstrated by several authors (Duponnois et al., 2001; Sall et al., 2020).

An additional important effect of amendment with slurries was the significant increase in the higher trophic levels Om4 (*Qudsianematidae*, *Eudorylaimus*, and *Dorylaimus*) and Om5 (*Thonus*). Thus, as observed in other studies, a regulatory effect called “top-down” appears in environments influenced by the addition of organic waste. The populations of nematodes belonging to lower trophic levels (microbivores) decreased, while the populations of higher trophic levels (omnivores) increased (Ferris and Bongers, 2006; Sall et al., 2020). Li et al. (2024b) found that the decrease in plant-parasitic nematodes (PPNs) could not be attributed to the top-down effect within the soil food web but rather to the toxic effects of biogas slurry, although they did not observe differences in the Structure Index (SI). In our study, we found significant differences in SI, mainly driven by the abundance of omnivores. This indicates that the biogas slurry (SMFP) added to the soil induced a more complex soil food web compared to other treatments

Conclusion

The objective of this study was to characterize the slurries resulting from the methanization of kitchen waste and to evaluate their fertilizing potential in sandy Senegalese soil. The mixture of food leftovers and potato peels (SMFP) demonstrated a high potential for providing nutrients for plant growth and microbial activity. In addition, the slurries increased the abundance of free-living nematodes while reducing the abundance of plant-parasitic nematodes, thereby contributing to the establishment of a ‘top-down’ regulatory effect that helps maintain the balance of the trophic structure.

This study presents a new approach to recycling organic waste from university cafeterias for agricultural use as an alternative to inorganic fertilization. It also suggests new directions for research and development.

Acknowledgements. This work was financed by the AFD (n° CSN151801G). Biogas activities were conducted through the action-research agreement between the NGO *Le Partenariat* and the *Université Gaston Berger de Saint-Louis*. Our thanks to the entire coordination team at *Le Partenariat*.

REFERENCES

[1] Adam, G., Duncan, H. (2001): Development of a sensitive and rapid method for the measurement of total microbial activity using fluorescein diacetate (FDA) in a range of soils. – Soil Biology & Biochemistry 33(7-8): 943-951.

[2] Alburquerque, J. A., de la Fuente, C., Bernal, M. P. (2012): Chemical properties of anaerobic digestates affecting C and N dynamics in amended soils. – Agric. Ecosyst. Environ. 160: 15-22. https://doi.org/10.1016/j.agee.2011.03.007.

[3] Andruschkewitsch, M., Wachendorf, C., Wachendorf, M. (2013): Effects of digestates from different biogas production systems on above and belowground grass growth and the nitrogen status of the plant-soil-system. – Grassland Science 59: 183-195.

[4] Baral, K. R., Labouriau, R., Olesen, J. E., Petersen, S. O. (2017): Nitrous oxide emissions and nitrogen use efficiency of manure and digestates applied to spring barley. – Agric. Ecosyst. Environ. 239: 188-198. Doi.org/10.1016/j.agee.2017.01.012.

[5] Bardgett, R. D., Van Der Putten, W. H. (2014): Belowground biodiversity and ecosystem functioning. – Nature 515: 505-511. doi: 10.1038/nature13855.

[6] Barzee, T. J., Edalati, A., El-Mashad, H., Wang, D., Scow, K., Zhang, R. (2019): Digestate Biofertilizers Support Similar or Higher Tomato Yields and Quality Than Mineral Fertilizer in a Subsurface Drip Fertigation System. – Front. Sustain. Food Syst. 3: 58. doi: 10.3389/fsufs.2019.00058.

[7] Bationo, A., Kihara, J., Vanlauwe, B., Waswa, B., Kimetu, J. (2007): Soil organic carbon dynamics, functions and management in West African agro-ecosystems. – Agricultural Systems 94: 13-25.

[8] Blanchart, E., Albrecht, A., Bernoux, M., Brauman, A., Chotte, J. L., Feller, C., Ganry, F., Hien, E., Manlay, R., Masse, D., Sall, S., Villenave C. (2007): Organic matter and biofunctioning in tropical sandy soils and implications for their management. – In: First management of tropical sandy soils for sustainable agriculture: a holistic approach for sustainable development of problem soils in the tropics. 536 p. Available at: http:// www.fao.org/docrep/010/ag125e/AG125E00.htm).

[9] Boizot, N., Charpentier, J. P. (2006): Méthode rapide d'évaluation du contenu en composés phénoliques des organes d'un arbre forestier. – Cahier Technique INRA, pp. 79-82.

[10] Bongers, T., Ferris, H. (1999): Nematode community structure as a bioindicator in environmental monitoring. – Trends in Ecology & Evolution 14(6): 224-228.

[11] Bongiorno, G., Bodenhausen, N., Bünemann, E. K., Brussaard, L., Geisen, S., Mäder, P., C. W., Walser, J. C., de Goede, R. G. M. (2019): Reduced tillage, but not organic matter input, increased nematode diversity and food web stability in European long-term field experiments. – Molecular Ecology 28: 4987-5005. https://doi.org/10.1111/mec.15270.

[12] Chauvin, C., Dorel, M., Villenave, C., Roger-Estrade, J., Thuries, L., Risède, J-M. (2015): Biochemical characteristics of cover crop litter affect the soil food web, organic matter decomposition, and regulation of plant-parasitic nematodes in a banana field soil. – Applied Soil Ecology 96: 131-140. DOI:10.1016/j.apsoil.2015.07.013.

[13] Chen, R. R., Blagodatskaya, E., Senbayram, M., Blagodatsky, S., Myachina, O., Dittert, K., Kuzyakov, Y. (2012): Decomposition of biogas residues in soil and their effects on microbial growth kinetics and enzyme activities. – Biomass Bioenergy 45: 221-229. doi.org/10.1016/j.biombioe.2012.06.014.

[14] Chojnacka, K., Moustakas, K. (2024): Anaerobic digestate management for carbon neutrality and fertilizer use: A review of current practices and future opportunities. – Biomass and Bioenergy 180: 106991. https://doi.org/10.1016/j.biombioe.2023.106991.

[15] Curry, N., Pillay, P. (2012): Biogas prediction and design of a food waste to energy system for the urban environment. – Renew. Energy 41: 200-209.

[16] Dia, A., Fall, C. S., Ndour, A., Sakho-Jimbira, M. S. (2009): Le Sénégal face à la crise énergétique mondiale: enjeux de l'émergence de la filière biocarburants. – Rapport, ISRA-Bame. 52p.

[17] Diagne, H. M., Nadieline, C. V., Ndiaye-Cissé, M. F., Ndiaye, N. A., Ndoye, I., Fall, S. (2016): Effets de biofertilisants et biodigestats des fientes de volaille et bouse de vache sur la croissance du maïs (*Zea mays*) et du sorgho (Sorghum sp). – Afrique Science.

[18] Dieng, K., Sall, S. N., Djigal, D., Diouf, D. (2023): Litter from native shrubs in the Senegal River Valley induces modifications in nematode communities and enzyme activities in cultivated sandy soils. – Communications in Soil Science and Plant Analysis 55(5). https://doi.org/10.1080/00103624.2023.2276256.

[19] Djigal, D., Chabrier, C., Duyck, P. F., Achard, R., Quénéhervé, P., Tixier, P. (2012): Cover crops alter the soil nematode food web in banana agroecosystems. – Soil Biology & Biochemistry 48: 142-150. doi: 10.1016/j.soilbio.2012.01.026.

[20] Drosg, B., Fuchs, W., Al, T., Madsen, S. M., Linke, B. (2015): Nutrient Recovery by Biogas Digestate Processing. – IEA Bioenergy: Paris, France.

[21] Duponnois, R., Chotte, J. L., Sall, S., Cadet, P. (2001): The effects of organic amendments on the interactions between a nematophagous fungus *Arthrobotrys oligospora* and the root knot nematodes *Meloidogyne mayaguensis* parazitising tomato plant. – Biology & Fertility of Soils 34(1): 1-6.

[22] Ehmann, A., Thumm, U., Lewandowski, I. (2018): Fertilizing potential of separated biogas digestates in annual and perennial biomass production systems. – Front. Sustain. Food Syst. 2: 1-14. doi.org/10.3389/fsufs.2018.00012.

[23] Feng, H., Qu, G. F., Ning, P., Xiong, X. F., Jia, L. J., Shi, Y. K., Zhang, J. (2011): The Resource Utilization of Anaerobic Fermentation Residue. – Procedia Environmental Sciences 11: 1092-1099. doi:10.1016/j.proenv.2011.12.165.

[24] Ferris, H., Bongers, T., de Goede, R. G. M. (2001): A framework for soil food web diagnostics: extension of the nematode faunal analysis concept. – Applied Soil Ecology 18: 13-29. https://doi.org/10.1016/S0929-1393(01)00152-4.

[25] Ferris, H., Bongers, T. (2006): Nematode indicators of organic enrichment. – Journal of Nematology 38: 3-12.

[26] Ferris, H. (2010): Form and function: metabolic footprints of nematodes in the soil food web. – European Journal of Soil Biology 46: 97-104.

[27] Ferris, H., Pocasangre, L. E., Serrano, E., Muñoz, J., Garcia, S., Perichi, G., Martinez, G. (2012): Diversity and complexity complement apparent competition: nematode assemblages in banana plantations. – Acta Oecologica 40: 11-18.

[28] Griffiths, B. S. (1994): Microbial-feeding nematodes and protozoa in soil: their effects on microbial activity and nitrogen mineralisation in decomposition hotspots and the rhizosphere. – Plant & Soil 164: 25-33.

[29] Gunnarsson, A., Bengtsson, F., Caspersen, S. (2010): Use efficiency of nitrogen from biodigested plant material by ryegrass. – Journal of Plant Nutrition & Soil Science 173: 113-119.

[30] Jamison, J., Khanal, S. K., Nguyen, N. H., Deenik, J. L. (2021): Assessing the Effects of Digestates and Combinations of Digestates and Fertilizer on Yield and Nutrient Use of Brassica Juncea (Kai Choy). – Agronomy 11: 509. doi.org/10.3390/agronomy11030509.

[31] Karaca, A., Cetin, S. C., Turgay, O. C., Kizilkaya, R. (2011): Soil enzymes as indication of soil quality. – In: Shukla, G., Varma, A. (eds.) Soil Enzymology. Berlin, Springer, pp. 119-148. doi: 10.1007/978-3-642-14225-3_7.

[32] Khanal, S. K. (2008): Anaerobic Biotechnology for Bioenergy Production: Principles and Applications. – Wiley-Blackwell: Hoboken, NJ, USA.

[33] Koninger, J., Lugato, E., Panagos, P., Kochupillai, M., Orgiazzi, A., Briones, M. J. I. (2021): Manure management and soil biodiversity: Towards more sustainable food systems in the EU. – Agricultural Systems 194: 103251. https://doi.org/10.1016/j.agsy.2021.103251.

[34] Kovačić, Đ., Lončarić, Z., Jović, J., Samac, D., Popović, B., Tišma, M. (2022): Digestate Management and Processing Practices: A Review. – Applied Sciences 12(18): 9216. https://doi.org/10.3390/app12189216.

[35] Kumar, R. R., Park, B. J., Cho, J. Y. (2013): Application and Environmental Risks of Livestock Manure. – J. Korean Soc Appl Biol Chem 56: 497-503. DOI 10.1007/s13765-013-3184-8.

[36] Kumar, A., Verma, L. M., Sharma, S., Singh, N. (2022): Overview on agricultural potentials of biogas slurry (BGS): applications, challenges, and solutions. – Biomass Convers. Biorefin. 13: 13729-13769. https://doi.org/10.1007/s13399-021-02215-0.

[37] Kuo, J., Dow, J. (2017): Biogas production from anaerobic digestion of food waste and relevant airquality implications. – J. of the Air and Waste Management Association 67: 1000-1011. Doi.org/10.1080/10962247.2017.1316326.

[38] Li, B. B., Smith, B., Hossain, Md. M. (2006): Extraction of phenolics from citrus peels. I. Solvent extraction method. – Separation and Purification Technology 48: 182-188.

[39] Li, Y., Park, S. Y., Zhu, J. (2011): Solid-state anaerobic digestion for methane production from organic waste. – Renewable and Sustainable Energy Reviews 15(1): 821-826.

[40] Li, A. R., Li, A. Q., Luo, C., Liu, B. (2024a): Assessing heavy metal contamination in *Amomum villosum* Lour. fruits from plantations in Southern China: soil-fungi-plant interactions. – Ecotoxicol. Environ. Saf. 269: 115789.

[41] Li, Y., Liu, B., Li, J., Zou, G., Xu, J., Du, L., Lang, Q., Zhao, X., Sun, Q. (2024b): Flooding soil with biogas slurry suppresses root-knot nematodes and alters soil nematode communities. – Heliyon 10: e30226.

[42] Liang, C., Balser, T. (2011): Microbial production of recalcitrant organic matter in global soils: implications for productivity and climate policy. – Nat. Rev. Microbiol. 9: 75. https://doi.org/10.1038/nrmicro2386-c1.

[43] Losak, T., Zatloukalova, A., Szostkova, M., Hlusek, J., Fryc, J., Vitez, T. (2011): Comparison of the effectiveness of digestate and mineral fertilisers on yields and quality of kohlrabi (*Brassica oleracea* L.). – Acta Universitatis Agriculturae et Silviculturae Mendelianae Brunensis (Czech Republic) 15(3): 117-122.

[44] Mahran, A., Tenuta, M., Lumactud, R. A., Daayf, F. (2009): Response of a soil nematode community to liquid hog manure and its acidification. – Appl. Soil Ecol. 43: 75-82.

[45] Makádi, M., Tomócsik, A., Orosz, V., Bogdányi, Z., Biró, B. (2007): Effect of a biogas-digestate and bentonite on some enzyme activities of the smended soils. – Cereal. Res. Commun. 35(2): 741-744. doi.org/10.1556/CRC.35.2007.2.144.

[46] Meng, Y., Zhang, L., Wang, L. Q., Shangguan, Y. X., Yang, Y., Li, X. F., Li, N. (2019): Cd and as accumulation of several leafy vegetables in soils contaminated by combined heavy metal. – J. Plant Nutrition and Fertilizers 25: 972-981.

[47] Meng, X., Ma, C., Petersen, S. O. (2022): Sensitive control of N_2O emissions and microbial community dynamics by organic fertilizer and soil interactions. – Biol. Fertil. Soils 58: 771-788. https://doi.org/10.1007/s00374-022-01662-9.

[48] Min, Y. Y., Toyota, K., Sato, E., Takada, A. (2011): Effects of anaerobically digested slurry on *Meloidogyne incognita* and *Pratylenchus penetrans* in tomato and radish production. – Appl. Environ. Soil Sci. 2011: 528712.

[49] Moletta, R. (1993): La digestion anaérobie: du plus petit au plus grand. – Biofutur 1: 16-25.

[50] Moletta, R. (2008): Méthanisation de la biomasse. – Paris: Techniques de l'Ingenieur. https://www.techniques-ingenieur.fr/base-documentaire/archives-th12/archives-bioprocedes-et-bioproductions-tiabi/archive-1/methanisation-de-la-biomasse-bio5100/.

[51] Möller, K., Müller, T. (2012): Effects of anaerobic digestion on digestate nutrient availability and crop growth: A review. – Engineering in Life Sciences 12: 242-257.

[52] Muscolo, A., Settineri, G., Papalia, T., Attinà, E., Basile, C., Panuccio, M. R. (2017): Anaerobic co-digestion of recalcitrant agricultural wastes: Characterizing of biochemical parameters of digestate and its impacts on soil ecosystem. – Science of the Total Environment 586: 746-752.

[53] Ndiaye, N. A. (2014): Caractérisation biochimique et pouvoir fertilisant (biofertilisant) de quelques substrats méthanisables de la zone de Sangalkam, Dakar. – FST, Département de Chimie, Master de chimie et biochimie des produits naturels, 40 p.

[54] Ndong, E. H., Labou, I. (2019): Étude expérimentale de la digestion anaérobique des déchets alimentaires en vue de déterminer l'intrant le plus rentable. – Rapport d'étude, Université Gaston Berger, Le Partenariat. Saint-Louis, 30p.

[55] Neher, D. A., Darby, B. J. (2009): General community indices that can be used for analysis of nematode assemblages. – In: Wilson, M., Kakouli-Duarte, T. (eds.). Nematodes as Environmental Indicators. CABI, Wallingford, UK, pp. 107-123. Doi :10.1079/9781845933852.0107

[56] Nkoa, R. (2014): Agricultural benefits and environmental risks of soil fertilization with anaerobic digestates: a review. – Agron. Sustain. Dev. 34: 473-492. https://doi.org/ 10.1007/s13593-013-0196-z.

[57] Oka, Y. (2010): Mechanisms of nematode suppression by organic soil amendments, A review. – Appl. Soil Ecol. 44: 101-115. https://doi.org/10.1016/j.apsoil.2009.11.003.

[58] Panuccio, M. R., Papalia, T., Attinà, E., Giuffrè, A., Muscolo, A. (2019): Use of Digestate as an Alternative to Mineral Fertilizer: Effects on Growth and Crop Quality. – Archives of Agronomy and Soil Science 65: 700-711. https://doi.org/10.1080/03650340.2018.1520980.

[59] PNB Sénégal (2016): Rapport d'activités semestriel janvier-juin 2016. – Half year report, 39p.

[60] Porazinska, D. L., Duncan, L. W., McSorley, R., Graham, J. H. (1999): Nematode communities as indicators of status and processes of a soil ecosystem influenced by agricultural management practices. – Applied Soil Ecology 13: 69-86.

[61] Qi, Q., Hu, C. X., Lin, J. H., Wang, X. H. Tang, C. X., Dai, Z. M., Xu, J. M. (2022): Contamination with multiple heavy metals decreases microbial diversity and favors generalists as the keystones in microbial occurrence networks. – Environ. Pollut. 306: 119406.

[62] Risberg, K., Cederlund, H., Pell, M., Arthurson, V., Schnürer, A. (2017): Comparative characterization of digestate versus pig slurry and cow manure – chemical composition and effects on soil microbial activity. – Waste Manag. 61: 529-538. https://doi.org/10.1016/j.wasman.2016.12.016.

[63] Robin, D. (1997): Intérêt de la caractérisation biochimique pour l'évaluation de la proportion de matière organique stable après décomposition dans le sol et la classification des produits organominéraux. – Agronomie 17: 157-171.

[64] Sall, S., Masse, D., Bernhard-Reversat, F., Guissé, A., Chotte, J. L (2003): Microbial activities during the early stage of laboratory decomposition of tropical leaf litters: the effect of interactions between litter quality and exogenous inorganic nitrogen. – Biology & Fertility of Soils 39: 103-111.

[65] Sall, S. N., Ngom, F. K., Diakhaté, S. (2020): Controlling plant-parasitic nematodes in sandy soil in the Senegal River Valley using composts based on potentially nematicidal plants. – Journal of Applied Biosciences 145: 14892-14901.

[66] Sánchez-Moreno, S., Nicola, N. L., Ferris, H., Zalom, F. G. (2009): Effects of agricultural management on nematode–mite assemblages: Soil food web indices as predictors of mite community composition. – Appl. Soil Ecol. 41: 107-117.

[67] Seck, H. (2019): Evaluation des gisements de déchets métanisables dans la ville de Saint-Louis: cas des marches de Teigndjiguène, de Ndar-Toute et de Pikine. – Master de géographie, Université Gaston Berger de Saint-Louis, 118 p.

[68] Seinhorst, J. W. (1962): Modifications of the elutriation method for extracting nematodes from soil. – Nematologica 8: 117-128.

[69] Sogn, T. A., Dragicevic, I., Linjordet, R., Krogstad, T., Eijsink, V. G., Eich-Greatorex, S. (2018): Recycling of biogas digestates in plant production: NPK fertilizer value and risk of leaching. – International Journal of Recycling of Organic Waste in Agriculture 7(1): 49-58.

[70] Sormana, J. D. (1992): Anaerobic Digestion of Chicken Dung. – Renewable Energy, 2nd World Energy Congress 3: 1292-1297.

[71] Tabarant, P., Villenave, C., Risede, J. M., Roger-Estrade, J., Thuries, L., Dorel, M. (2011): Effects of four organic amendments on banana parasitic nematodes and soil nematode communities. – Applied Soil Ecology 49: 59-67.

[72] Tambone, F., Scaglia, B., D’Imporzano, G., Schievano, A., Orzi, V., Salati, S., Adani, F. (2010): Assessing amendment and fertilizing properties of digestates from anaerobic digestion through a comparative study with digested sludge and compost. – Chemosphere 81(5): 577-583.

[73] Tambone, F., Adani, F. (2017): Nitrogen mineralization from digestate in comparison to sewage sludge, compost and urea in a laboratory incubated soil experiment. – Journal of Plant Nutrition & Soil Science 180: 355-365. DOI:10.1002/jpln.201600241.

[74] Tampio, E., Salo, T., Rintala, J. (2016): Agronomic characteristics of five different urban waste digestates. – Journal Environmental Management 169: 293-302.

[75] Tan, F., Zhu, Q., Guo, X., He, L. (2021): Effects of digestate on biomass of a selected energy crop and soil properties. – Journal of Science of Food and Agriculture 101: 927-936. https://doi.org/10.1002/jsfa.10700.

[76] van den Hoogen, J., Geisen, S., Routh, D. et al. (2019): Soil nematode abundance and functional group composition at a global scale. – Nature 572: 194-198. Doi:10.1038/s41586-019-1418-6.

[77] van Midden, C., Harris, J., Shaw, L., Sizmur, T., Pawlett, T. M. (2023): The impact of anaerobic digestate on soil life: A review. – Applied Soil Ecology 191: 105066.

[78] van Soest, P. J., Robertson, J. B., Lewis, B. A. (1991): Methods for dietary fiber neutral detergent and nonstarch polysaccharides in relation to animal nutrition. – Dairy Science 74: 3583-3597.

[79] Villenave, C., Saj, S., Pablo, L-A., Sall, S., Djigal, D., Chotte, J-L., Bonzi, M. (2010): Influence of long-term organic and mineral fertilization on soil nematofauna when growing Sorghum bicolor in Burkina Faso. – Biology & Fertility of Soils 46: 659-670.

[80] Wang, Y., Chikamatsu, S., Gegen, T., Sawada, K., Toyota, K., Riya, S., Hosomi, M. (2019): Application of biogas digestate with rice straw mitigates nitrate leaching potential and suppresses root-knot nematode (*Meloidogyne incognita*). – Agronomy 9: 227. DOI:10.3390/agronomy9050227.

[81] Wang, N., Wang, X. X., Chen, L., Liu, H. J., Wu, Y. F., Huang, M., Fang, L. C. (2024): Biological roles of soil microbial consortium on promoting safe crop production in heavy metal(loid) contaminated soil: A systematic review. – Sci. Total Environ. 912: 168994.

[82] Wentzel, S., Joergensen, R. G. (2016): Effects of biogas and raw slurries on grass growth and soil microbial indices. – Journal of Plant Nutrition & Soil Science 179: 215-222.

[83] Westphal, A., Kücke, M., Heuer, H. (2016): Soil amendment with digestate from bioenergy fermenters for mitigating damage to Beta vulgaris subspp. by *Heterodera schachtii*. – Appl. Soil Ecol. 99: 129-136.

[84] Yeates, G. W., Bongers, T., de Goede, R. G. M., Freckman, D. W., Georgieva, S. S. (1993): Feeding habits in soil nematode families and genera-an outline for soil ecologists. – Journal of Nematology 25: 315-331.