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A Model for Organic Matter of Fields Fertilized with Anaerobic Digestion Reactor Effluent

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Abstract: Soil fertility in agriculture is maintained by recalcitrant organic matter in manures and crop residues that are recycled to the fields. In some countries crop residues are burned in the field and in others these are collected and burned in furnaces as a source of renewable energy. These practices reduce the organic matter of the soils which is essential for their fertility. Anaerobic digestion installations convert manures and crop residues (mainly straw) into carbon dioxide, methane and other components. There remains a residue of recalcitrant organic material. The methane is is used as a source of renewable energy. The objective of this study is to determine the reduction in soil organic matter due to the anaerobic digestion of straw and cattle manure. The dynamics of the decay process of straw in the soil has been applied to the anaerobic digestion of these substrates. The decay of the organic material in the effluent of anaerobic digestion installations recycled to the fields has been modelled and compared to the decay of the substrates in the soil, without anaerobic digestion. The few field data on the effect of the effluent of anaerobic digestion reactor show no or little variation, compared to those when the substrates are directly applied to the fields. Around 45% of the energy content of straw and manures can be used as a source of renewable energy. The contribution to the soil organic matter of recycled effluent is 85% of that of the substrates directly applied to the soil.

Keywords: Soil Organic Matter, Renewable Energy, Anaerobic Digestion, Straw, Cattle Manure, Bio-methane

1. Introduction

Traditionally, crop residues are burned in the fields. Potassium and phosphate (fertilisers) in the ash are then directly available for the next crop [1]. Over the years, the soil organic matter [SOM] is reduced [2].

SOM in agricultural fields consists of decaying crop residues, roots and dead organisms [3, 4]. Archea, microbes and fungi transform this in carbon dioxide, water, and humic substances. SOM contains more carbon than global above-ground vegetation and the atmosphere combined [5, 6].

Nutrient exchanges between SOM, water, and soil are essential to soil fertility and need to be maintained. When the soil is exploited for crop production without restoring the organic matter and nutrient contents, the nutrient cycles are broken, soil fertility declines, and the balance in the agro-ecosystem is destroyed [7].

Currently, two thirds of the fields under maize and wheat cultivation have a SOM content of less than 2%, the lower bound for optimal crop production [8]. Further reduction of SOM in agricultural lands should thus be avoided.

The field burning of crop residues has stopped in some countries and is of a concern in others [9]. Straw, replacing coal, is instead burned or gasified in boilers and furnaces to generate heat and power [10, 11].

Various governments subside the building and operation of anaerobic digestion [AD] plants using organic materials from waste water clean-up, food processing and agricultural residues and energy crops [12-14]. The methane containing gas (biogas) is then burned in furnaces to produce heat and power. [15]. The AD of straw can replace the burning of straw as source of renewable energy renewable energy [16].

The German government requires bookkeeping of SOM. The guidelines suggest that using the effluent of AD reactors instead of straw and manure to fertilize the crops results longterm in a reduction of 50% in the SOM [17]. Newer research indicates, however, that AD has little effect on the SOM [18].

This paper describes a model for the SOM on fields fertilised with AD reactor effluent. This model assumes, that the decomposition process of organic material during AD is similar to that of the raw material in the fields.

2. Anaerobic Digestion

Anaerobic digestion is a naturally occurring process in swamps and is collected as heating or cooking fuel [19, 20]. This process has been adapted to generate heat and power from treated wastewater, food processing residues, agricultural residues and manures. In AD, organic matter or volatile solids (VS) is converted under exclusion of oxygen into carbon dioxide, methane, ammonia, sulphur dioxide and a number of other components. There remains a residue of water, ammonia, volatile acids and recalcitrant organic matter [21, 22].

The methane yield for different substrates can be determined by biomethane potential assays [BMP] [23, 24]. A BMP is performed by mixing the material with effluent from an operating AD reactor. The methane produced is measured at different times. An equation has been developed that describes the methane yield (y_{ch4}) in a BMP as a function of time using two exponential functions (A fast component and a slow component).

$$y_{CH4}= a*(1-R)*(1-^{(-b*c*t)})+a*R*(1-e^{(-b*d*t)}) \quad (1)$$

a=0.415 m^3/kg VS, this is the theoretical methane yield for carbohydrates [25].

b=is a constant fitted to the BMP tests, reflecting the hydrolysis rate of the substrate

c=2.1 y^{-1}. is a multiplier to the the fast decay constant

d=0.13 y^{-1}. is a multiplier to the slow decay constant

e=2.72 (natural logarithm)

R is the fraction of recalcitrant organic matter in the reactor substrate and fitted to the methane production curves in the BMP tests.

a-e and R are constants

t is the digestion time in years

Time dependent results of a number of BMP tests are available [26-30]. The recalcitrant fraction and the hydrolysis rate of equation 1 have been fitted to these time series. There is some variability in b and R (Table 1 and 2). Cattle manure has also some variability in these constants depending of the type of fodder [31].

Table 1. *Klason lignin and fraction of recalcitrant material R in straw.*

Substrate	Klason lignin KL	Recalcitrant fraction R	Ratio R/KL	Author Reference
Wheat straw	0.24	0.5	2,0	[35] Antonczyk
Wheat straw	0.17	0.35	2,0	[48] Dumas
Wheat straw	0.18	0.35	2,0	[49] Horvath
Wheat straw	0.29	0.6	2,0	[50] Sambusiti
Wheat straw	0.27	0.4	1.5	[51] Awais
Cattle manure	0.15	0.25	1.7	[51] Awais

Table 2. *Recalcitrant fraction of straw and cattle manure.*

Substrate	Fast tike constant b y^{-1}	Recalcitrant fraction R	Author reference
Wheat straw 1mm AD	10	0.20	[29] Slotjuk
Wheat straw 10 mm AD	4	0.20	[29] Slotjuk
Wheat straw AD	10	0.35	[30] Xavier
Wheat straw in soil	1	0.33	[26] Sauerbeck
Cattle manure slurry AD	10	0.58	[28] Kool
Cattle manure slurry in soil	1	0.58	[27] Verloop

3. A Model for the Anaerobic Digestion of Straw

Straw is a residue of the harvest of cereals (mainly wheat and maize) burned on the field or removed for other uses. Straw contains on average 30 – 45% cellulose, 20 – 25% hemicellulose, 15 – 20% lignin, as well as a number of minor organic compounds [32, 33].

Archaea, microbes and fungi decompose straw under aerobic conditions in the field, with the emissions of carbon-dioxide, trace gasses, water, and ash.

Straw plowed under releases two thirds of its carbon fixed during the growing season in the first year of decay. The other third is released in the next ten years.

Experiments on the decay of straw in the soil have been executed with radioactive labeled straw [25, 34]. The decay of straw in the fields has been fitted with the sum of two exponential functions (a slow one and a fast one) [35]. Only the slow component with a decay constant of about eight years contributes to the SOM. Other data suggest a slow decay constant of ten to forty years [36, 37].

Straw as substrate for AD has been reported for a number of commercial facilities [9, 38-41]. The model for AD in this paper is based on four hypothesis:

During AD, the same decay process occurs as in the soil, except this process is faster, due to higher temperatures and the availability of macro and micronutrients (N, P, Fe, Zn, Co, Cu, Mn, Mo, Ni, B, S, and W) [42-45]. These nutrients are necessary for the multiplication of archaea and microbes decomposing the straw.

The decomposition of straw into carbon dioxide, methane, water and recalcitrant matter can be described by the sum of two exponential functions.

Part of the cellulose and hemicellulose is shielded by lignin from the attack by archaea and microbes and with lignin forms the recalcitrant matter.

The shielded part of cellulose and hemicellulose is about double that of the Klason lignin (Table 1) [37, 46-51].

In order to calculate the contribution to SOM of the effluent of the AD reactor, we assume an effective reaction time of bt=1. The real time depends on the efficacy of the AD process. The contribution to the SOM of straw plowed under, can be calculated assuming bt=1 and R=0.33 [25, 29]. Then, 90% of the easily degradable material (the fraction with the short decomposition time) is converted into methane, carbon dioxide and water. The recalcitrant matter in the effluent distributed on the fields contributes to the SOM. The organic matter in the effluents is:

$$OM_{ad}=VS*(1-R)*e^{-c}+R*e^{-d} \tag{2}$$

VS is the volatile solids (organic matter) of the substrate entering the AD reactors

The effluent should be spread to the field where the straw has come from, and after one year in the soil, the organic matter is reduced by an extra factor of e^{-d}, neglecting the small contribution of easily degradable material:

$$OM^{1}=VS*R*e^{-d}*e^{-d} \tag{3}$$

after n years in the soil, this is:

$$OM^{n}=VS*R*e^{-d}*e^{-n*d} \tag{4}$$

After the application in each year of the same amount of organic matter, the SOM is:

$$SOM_{ad}=VS*R*e^{-d}*(1+e^{-d}+e^{-2*d}+e^{-3d}+\ldots\ldots \tag{5}$$

and:

$$SOM_{ad}=VS*R*e^{-2d}/(1-e^{-d}) \tag{6}$$

and for: R=0.33 ($Table$ 2)

$$SOM_{ad}=VS*2.1 \tag{7}$$

and:

$$y_{CH4}=0.25\ m^3/kg\ VS \tag{8}$$

For straw left in the field, we obtain:

$$SOM = VS*((1-R)*e^{-c}+R*e^{-d}/(1-e^{-d}) \tag{9}$$

and:

$$SOM=VS*2.5 \tag{10}$$

The ratio of SOM between fields fertilized by the effluent of AD reactors with straw as substrate and that where the straw is left to decay in the field after the harvest is:

$$SOM_{ad}/SOM=0.85 \tag{11}$$

4. A Model for the Anaerobic Digestion of Cattle Manure

Cattle manure contains on average 15-30% cellulose, 10-28% hemicellulose, 20-33% lignin, as well as a number of minor organic compounds [52-58].

A model from Wageningen University and Research, describes the SOM of fields, fertilised over a number of years with cattle manure [27].

This model can be simplified, to the sum of the two exponential functions and applied for the SOM of fields fertilised with the effluent of cattle manure treated by AD. with R=0.58 equation 6 gives:

$$SOM_{ad}=VS*3.7 \tag{12}$$

For manure spread directly in the field after one year decay, (9) gives:

$$SOM=VS*3.8 \tag{13}$$

and for the ratio of SOM of fields fertilised with the effluent of AD reactors with manure as substrate and those fields where manure is spread without prior AD is:

$$SOM_{ad}/SOM=0.98 \tag{14}$$

5. Energy Recovery by the AD of Straw

Straw tested in Finland has a higher heating value of 17 MJ/kg [59] and a VS content of 70%. The higher heating value of VS is 24 MJ/kg. The higher heating value of methane is 40 MJ/m3 [60]. Energy recovery is 12 MJ/m^3 or 50% of the higher heating value of straw.

Biomethane can be obtained by removing carbon dioxide from the AD gas [61]. The different upgrading methods require about 0.9 MJ_e/m^3 methane or 1.5 MJ_{th}/m^3 [62]. Combined cycle power stations using bio-methane have efficiencies of 60% [63]. The overall efficiency is 25%. Direct bur- ning of straw has an efficiency of 26% [64].

The existing infrastructure for the distribution of natural gas can be used [65]. The removed carbon dioxide can be stored permanently as carbonate geologically or as biochar [66-68].

6. Discussion

AD reactor effluent of cattle manure slurry was applied for a period of 15 years to a field of the experimental dairy farm of Wageningen University and Research. This field showed a slight increase in SOM from 4.3% to 4.5%. [69]. Control fields showed a constant SOM content over a period of 20 years [27]. No information was given about the volumes of digested cattle manure and undigested raw manure distributed to the fields. It is likely that more effluent was applied than unprocessed manure due to limitation in the application of N-compounds (ammonia and organic bound nitrogen).

The AD installation at that site produced in the test period 0.26 m^3 methane /kg VS at an average retention time of 75 days [28]. BMP tests are not available, but the recalcitrant fraction is estimated, to be 0.58 assuming a hydrolysis rate for cattle manure of 10.

Volatile fatty acids in the manure contribute to the methane yield in BLP tests, but are not measured in the VS determination [70] and in the determination of the SOM. Volatile fatty acids can be more than 10% of the VS (depending on the storage time at the farm) [30, 71].

In field experiments, no differences were found in the soil total C content after four years of application of AD effluent and manures [72, 73].

There is some information available of fresh and digested cattle manure after one year of decay in the soil [74, 75]. The data of Thomson et al. [74] are inconsistent as the recalcitrant fraction in digested manure should be higher than that in fresh manure. The experimental procedures, however, have not been described.

It should be noted that SOM determinations are not accurate (>0.1%), due to analytical, spatial and temporal variations [76, 77].

7. Conclusions

Around 45% of the energy content of straw and manures can be used as a source of renewable energy. Overall, conversion efficiency to electricity is 25%, compared to 26% in straw fired power stations [65].

The contribution to the soil organic matter SOM of recycled effluent is 85% of the substrates.

The AD of straw is preferred over burning of straw. The AD of agricultural residues and manures should be promoted in those regions where the SOM is higher than 2%. AD of straw and manure is possible, where the SOM is lower than 2% when the loss of SOM is compensated by supplementary addition of green manures and compost [78-82].

Abbreviations

AD Anaerobic Digestion
BMP Bio Methane Potential assay
SOM Soil Organic Matter
VS Volatile Solids (Organic matter)

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