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Co-ensiling, co-composting and anaerobic co-digestion of vegetable crop residues: Product stability and effect on soil carbon and nitrogen dynamics

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ABSTRACT

Nitrogen (N)-rich vegetable crop residues left in the field may result in a high risk for N losses during autumn. Removal and conservation of these residues followed by reuse in the field could contribute to improved recycling of nutrients, but some form of processing is required to allow storage before re-application. We have compared co-ensiling, co-composting and anaerobic co-digestion as conservation and valorization options for fresh crop residues. We studied (1) the product quality and stability and (2) the short-term effects of application of these silages, composts and digestates on soil C and N mineralization and N_2O emissions. Ensiling resulted in highly biodegradable products with a low pH (4.2-5.2) and more NH_4^+-N compared to composts. Consequently, soil incorporation of silages resulted in higher net C mineralization (up to 47% after 82 days) and microbial biomass C (up to 93 μg C g^{-1} soil after six weeks), and temporary N immobilization (up to 42 mg kg^{-1} soil). Digestates and composts led to lower C mineralization rates (between 2 and 27%) and microbial biomass C (max. 51 μg C g^{-1} soil) and no net N immobilization nor mineralization. Application of digestates resulted in high mineral N contents (47–192 mg kg^{-1} soil) and a decrease of the soil pH. In all three treatments, short-term N_2O losses after soil application were very small (<0.11 kg N ha^{-1} after 12 days). Growers can choose the most appropriate treatment option and application moment and location, depending on the local soil and crop requirements and the on-farm facilities. Furthermore, we conclude that the parameters biodegradation potential (based on the biochemical composition) and oxygen uptake rate have potential as less time-consuming proxies for C mineralization to assess the product stability.

1. Introduction

After harvest in autumn, vegetable crop residues left on the field may cause nitrate leaching because biomass with a high nitrogen (N) content and low C/N ratio is remaining (Chaves et al., 2007). Additionally, N mineralization and nitrification rates are still relatively high in autumn (De Neve and Hofman, 1996). For these reasons, removal of these residues from the field is usually recommended. Preserving and valorizing (nutrients from) field-collected residues and crop residues generated off-field (e.g., from on-farm leek cleaning) is quite a challenge given their tendency to decay quickly. Possible conservation and valorization options for nutrients of crop residues include co-composting, anaerobic co-digestion (AD) and co-ensiling with drier bulking agents more rich in C. Reuse of crop residues for producing organic fertilizers and soil improvers as composts, digestates and silages, closes nutrient cycles locally and improves or maintains soil quality.

Co-composting of crop residues stabilizes and sanitizes organic material, which generates a valuable soil improver and slow-release fertilizer. The effect of compost amendment on soil

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dynamics is well documented: generally the plant-available N and C mineralization are low, which decreases the risk for leaching to soil and surface waters (Amlinger et al., 2003) and helps to increase topsoil organic C (D'Hose et al., 2016). Anaerobic co-digestion of manure with agricultural wastes is a technology for producing biogas as a renewable energy source (Möller, 2015). The remaining digestate can be reused as a fertilizer. More research is needed on the influence of feedstock on digestate composition and the effects of digestate application on soil dynamics (Möller, 2015). Furthermore, to the best of our knowledge, there are no studies on the effect of co-digesting of silages based on vegetable crop residues. Recent research has shown that co-ensiling of vegetable crop residues with maize straw is a simple and low-cost strategy to preserve vegetable crop residues over winter (Agneessens et al., 2015). The co-ensiled crop residues can then be used either directly as fertilizer, as feedstock in composting and biogas plants or as a feed supplement for livestock (Agneessens et al., 2014).

To the best of our knowledge, this paper is the first to compare how different methods of processing the same vegetable crop residues result in products with different levels of stability and greatly different effects on soil N and C dynamics. This paper is innovative as it compares co-ensiling of fresh crop residues as a novel and alternative low-cost conservation and valorization option with (1) fresh crop residues (considered here as *negative reference*), and with (2) co-composting and (3) AD of crop residues after field removal (both considered here as *positive references*), thereby producing fertilizers and soil improvers. Composts and digestates were included as positive reference materials, as more is known about their product stability and their effects on soil N and C dynamics, i.e., they are characterized by stable OM and high product stability, and show little C and N mineralization after soil application. Therefore, we hypothesized that (i) silages would be more readily degradable products than composts and digestates; and (ii) silage amendment would result in N immobilization, higher C mineralization and higher N_2O emissions compared to compost and digestate application as soil amendment. To test the first hypothesis, we compared different stability parameters, i.e., C/N ratio, biodegradation potential, oxygen uptake rate (OUR) and C mineralization. To test the second hypothesis, N and C mineralization and N_2O emissions were monitored during lab incubations over a period of several months.

2. Materials and methods

2.1. Description of co-ensiling, AD and co-composting trials

This study included two trials. In trial 1, crop residues from leek (*Allium porrum* L.) and white cabbage (*Brassica oleracea convar. capitata var. Alba*) were collected in fall 2012. Residues of white cabbage were mechanically harvested with a tractor-pulled Peruzzo1600 flail cutter. Leek residues resulting from cleaning and preparing leek for the fresh market were collected on-farm. In trial 2 similar fresh leek residues (*FL*) were collected in January 2014. Co-composting was executed at field scale, while co-ensiling and anaerobic digestion were simulated at lab scale. Composting and ensiling were conducted at the Institute of Agricultural and Fisheries Research (ILVO) in Merelbeke, Belgium, while AD was executed in a lab-scale batch test at Inagro, Rumbeke-Beitem, Belgium.

2.1.1. Co-ensiling and AD processes

The vegetable crop residues were cut by hand (5 cm × 5 cm) and mixed in a 1:1 (trial 1) and 60:40 v/v ratio (trial 2) with chopped maize straw (<1 cm, mechanically chopped stems and leaves only). The mixtures were ensilaged in silage buckets of 15 L (Agriton, Mesen, Belgium) in four replicates per treatment. The buckets were sealed (oxygen-free) and contained a reservoir to collect possible leachate from the silage. The silages with cabbage and leek from trial 1 are referred to below as *CS1* and *LS1*, respectively, and the silage with leek from trial 2 as *LS2*. The packing density of the silages in the 15 L buckets at the start of the silage experiment was 616.2, 445.5 and 522.3 g/L *for CS1*, *LS1*, and *LS2* respectively. The characteristics of the crop residues and maize straw at the start of ensiling is given in Table A1 Appendix A. After ensiling, the silages were anaerobically digested at an organic loading rate of 5 g/L in three parallel lab-scale batch tests at 38 °C for 45 days, i.e., until no further increase in methane production was observed. At the start of the AD batch test, silages were mixed with inoculum (i.e., digestate from a previous batch in a full-scale digester that was incubated for 1 week at 38 °C) to simulate the environment of a digester. The digestates with silage of cabbage and leek from trial 1 are referred to below as *CD1* and *LD1*, respectively, and the digestate with silage of leek from trial 2 as *LD2*. The rationale of using silage as starting material for AD instead of fresh vegetable crop residues is that fresh vegetable crop residues are only available in restricted periods during the year, and decay fast, reducing the potential for storage. The crop residues were ensiled because this conserves the biomass, as such a continuous input to the digester is possible. Of course, this is an extra processing step, increasing the costs.

2.1.2. Co-composting processes

The leek and cabbage residues were co-composted on a concrete pad in a windrow composting system. To ensure a good composting process, vegetable crop residues (low DM and high N content), should be co-composted with C-rich bulking agents to decrease the moisture content, increase the C/N ratio and minimize N losses during composting (Nolan et al., 2011). For trial 1, the C-rich bulking agents consisted of a mixture of wheat straw (1% (v/v)), maize straw (21% (v/v)), poplar bark (16% (v/v)) and wood chips (19% (v/v)), which was mixed with cabbage residues (*CC1)* on November 26th 2012 and with leek residues (*LC1)* on December 5th 2012 (each 43% (v/v)). In the second trial, on January 16th 2014, the leek residues (17% (v/v)) were mixed with maize straw (28% (v/v)), wood bark (11% (v/v)) and either chopped heath biomass ($LC2_{heath}$) or strawberry substrate ($LC2_{strawberry}$) (44% (v/v)). Chopped heath biomass (i.e., biomass from heathland management) or used strawberry substrate (i.e., growing medium at the end of the growing season of strawberry culture), were tested as an inexpensive alternative for wood chips. The feedstock materials were combined to obtain feedstock mixtures with a similar C/N ratio per trial (C/N around 43 in trial 1 and 30 in trial 2). The piles were turned using a compost turner (TG 301, Gujer Innotec AG, Switzerland) to maintain aerobic conditions and ensure optimum moisture content. LC1 and LC2 were turned eight times, while $LC2_{heath}$ and $LC2_{strawberry}$ were turned 10 and 12 times, respectively. The compost piles were covered with a gas-permeable geotextile (TopTex) to protect them from precipitation. Geotextiles were used to avoid too high evaporation from the piles reducing the moisture content below optimal levels for composting, in combination with avoiding too high water influx during rain events, to avoid too wet composts for optimal composting. The piles were 12 m long, 3 m wide and 1.5 m high. Temperature (Digital Thermometer GTH1150) and CO_2 (Brigon Messtechnik D-63110 Rodgau) were monitored as the average of four point measurements along the length of the piles. In trial 1, pile temperatures reached a maximum (>65 °C) shortly after the composting process started (Fig. A1 in Appendix A). The CO_2 concentrations peaked at the beginning of the process and were under the detection limit after two weeks. In trial 2, pile temperatures of $LC2_{heath}$ reached a maximum of 57 °C after eight days, whereas in $LC2_{strawberry}$ temperatures remained ≤42 °C (Fig. A1 in Appendix A). Therefore, extra fresh leek residues were added to both piles on day 19 to stimulate the microbial activity and increase temper-