Reduction of ammonia emissions from laying hen manure in a closed composting process using gas-permeable membrane technology

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SUPPLEMENTARY MATERIAL

Table S1. Physicochemical parameters of the initial product mixture samples in each treatment.

Parameters*	Control	System 1 (S1)	System 2 (S2)
MC (%) [a]	51,9 ± 0,9	58,9 ± 7,4	60,0 ± 0,4
VS (%) [b]	72,6 ± 3,1	82,2 ± 0,4	73,9 ± 0,9
pH [a]	6,2 ± 0,1	6,8 ± 0,0	6,6 ± 0,0
EC ($mS \cdot cm^{-1}$) [a]	4,47 ± 0,40	2,86 ± 0,03	3,08 ± 0,02
TN (%) [b]	2,78 ± 0,02	2,93 ± 0,01	3,15 ± 0,02
NH_4-N (%) [a]	0,19 ± 0,00	0,14 ± 0,01	0,16 ± 0,00
P_2O_5 (%) [b]	0,80 ± 0,02	0,60 ± 0,04	0,73 ± 0,02
P assim (%) [b]	0,08 ± 0,01	0,06 ± 0,00	0,08 ± 0,00
K ($mg \cdot kg^{-1}$) [b]	11515 ± 422	9053 ± 494	9624 ± 155
Na ($mg \cdot kg^{-1}$) [b]	1461 ± 68	1286 ± 74	1214 ± 34
Ca ($mg \cdot kg^{-1}$) [b]	48389 ± 2890	38673 ± 2744	40644 ± 701
Mg ($mg \cdot kg^{-1}$) [b]	4142 ± 179	3066 ± 159	3317 ± 70
K asim ($mg \cdot kg^{-1}$) [b]	16899 ± 2093	14856 ± 75	16336 ± 1707
Na asim ($mg \cdot kg^{-1}$) [b]	2148 ± 276	2281 ± 6	2413 ± 103
Ca asim ($mg \cdot kg^{-1}$) [b]	7152 ± 732	5211 ± 89	4398 ± 98
Mg asim ($mg \cdot kg^{-1}$) [b]	3998 ± 514	3275 ± 5	1915 ± 28
Cu ($mg \cdot kg^{-1}$) [b]	30 ± 1,2	19,8 ± 0,8	22 ± 0,4
Fe ($mg \cdot kg^{-1}$) [b]	434 ± 31	1048 ± 70	842 ± 30
Mn ($mg \cdot kg^{-1}$) [b]	182 ± 4	135 ± 4	144 ± 4
Zn ($mg \cdot kg^{-1}$) [b]	199 ± 17	150 ± 13	158 ± 7
Hg ($\mu g \cdot kg^{-1}$) [b]	5,3 ± 0,1	4,7 ± 0,1	5,8 ± 0,1

* Moisture content (MC), volatile solids (VS), electrical conductivity (EC), total nitrogen (NT), ammoniacal nitrogen (NH_4-N), total phosphorus (P_2O_5), assimilable phosphorus (P assim). Values are expressed as mean ± standard deviation (n = 3).

[a] Measurement based on wet weight; [b] Measurement based on dry weight.

Table S2. Physicochemical parameters of the product mixture samples at the end of the experiment (after 44 days) in each treatment.

Parameters*	Control	System 1 (S1)	System 2 (S2)
MC (%) [a]	55,0 ± 1,4	60,4 ± 0,3	56,3 ± 1,3
VS (%) [b]	53,9 ± 1,9	63,2 ± 1,5	67,0 ± 4,6
pH [a]	8,5 ± 0,1	8,6 ± 0,3	8,6 ± 0,0
EC ($mS \cdot cm^{-1}$) [a]	2,53 ± 0,08	2,65 ± 0,18	4,26 ± 0,31
TN (%) [b]	2,39 ± 0,02	2,72 ± 0,02	2,99 ± 0,05
NH_4-N (%) [a]	0,05 ± 0,00	0,16 ± 0,02	0,19 ± 0,03
P_2O_5 (%) [b]	1,22 ± 0,06	0,99 ± 0,05	1,08 ± 0,04
P assim (%) [b]	0,13 ± 0,01	0,14 ± 0,01	0,12 ± 0,00
K ($mg \cdot kg^{-1}$) [b]	12085 ± 945	19045 ± 688	13410 ± 507
Na ($mg \cdot kg^{-1}$) [b]	1622 ± 275	2983 ± 107	2200 ± 85
Ca ($mg \cdot kg^{-1}$) [b]	81379 ± 19310	57930 ± 3247	70978 ± 2924
Mg ($mg \cdot kg^{-1}$) [b]	6075 ± 976	4735 ± 229	5283 ± 194
K asim ($mg \cdot kg^{-1}$) [b]	21320 ± 212	25592 ± 666	18302 ± 922
Na asim ($mg \cdot kg^{-1}$) [b]	2461 ± 37	3871 ± 116	2879 ± 94
Ca asim ($mg \cdot kg^{-1}$) [b]	6972 ± 32	4142 ± 149	4539 ± 116
Mg asim ($mg \cdot kg^{-1}$) [b]	3250 ± 168	1858 ± 69	3642 ± 103
Cu ($mg \cdot kg^{-1}$) [b]	40 ± 4,1	35 ± 1,0	34 ± 1,0
Fe ($mg \cdot kg^{-1}$) [b]	632 ± 74	1084 ± 7	918 ± 48
Mn ($mg \cdot kg^{-1}$) [b]	265 ± 42	214 ± 13	234 ± 12
Zn ($mg \cdot kg^{-1}$) [b]	278 ± 31	244 ± 15	242 ± 6
Hg ($\mu g \cdot kg^{-1}$) [b]	6,3 ± 0,1	8,4 ± 0,3	5,4 ± 0,0

* Moisture content (MC), volatile solids (VS), electrical conductivity (EC), total nitrogen (NT), ammoniacal nitrogen (NH_4-N), total phosphorus (P_2O_5), assimilable phosphorus (P assim). Values are expressed as mean ± standard deviation (n = 3).

[a] Measurement based on wet weight; [b] Measurement based on dry weight.

Economic assessment of system 1

Assumptions:

- The composting unit had a volume of 3.7 m^3 and treated 5.65 kg N from a mixture of manure and straw (470 kg chicken manure + wheat straw). The average N-NH_3 production was 0.29 $kg\ N \cdot m^{-3}$.
- Each batch of the composting process has a duration of 44 days.
- 76% of the TAN emissions in the composting unit are recovered in the form of $(NH_4)_2SO_4$.
- The maximum recovery rate is 6.9 g TAN $m^{-2}\ day^{-1}$.
- The cost of the closed aerobic composter (7,767 €) was excluded from the analysis.
- The costs of the modifications made to the standard closed aerobic composter are itemized in Table S3, and account for 6084.5 €.
- 1.96 m^2 of membrane were used at a cost of 156.25 $€ \cdot m^{-2}$ (market price in 2020). A 20% replacement per year has been considered.
- The annualised costs of the equipment are calculated assuming a lifespan of 10 years and an interest rate of 8% [97].
- The energy consumption was estimated at 15.7 kWh day^{-1}.
- It is estimated that the compost produced is sold at 20 $€ \cdot tonne^{-1}$ (average market price [1]).

Table S3. Estimated costs for the modifications made to the standard closed aerobic composter in system S1.

Equipment	Cost (€)
PLC control	700
HMI screen	345
Acid pump	610
Gas detectors	1,950
Temperature and pH probes	1,250
Flow probe	350
Potentiometer for controlling flowrate	350
Acid tank (60 L)	28.5
Piping	164
Steel rods and clamps for membranes mounting	31
Membranes	306
Total	6,084.5 €

Table S4. Summary of capital expenses, operating expenses and operating revenues for a closed aerobic composting system with an NH_3 capture system based on GPM technology directly installed in the aerobic composter.

Capital Expenses		
	Initial Investment (€)	**Annualized Costs: 8% interest, 10-year life (€/year)**
Nitrogen recovery prototype	6,084.5	907
Operational Expenses		
		Annual expenses (€/year)
Membranes replacement (20%)	-	61
Chemicals (H_2SO_4)	-	4
Power (ΣkWh)	-	626
Total operational annual costs	-	691
Total annualized cost		1598
Revenue (€/year)		
Sale of compost		38
Recovered nitrogen: 6.74 kg N/year (€ 2.36/kg N)		16
Net annual cost		**1,544**

Economic assessment of system 2

Assumptions:

- The composting unit had a volume of 3.7 m^3 and treated 6.35 kg N from a mixture of manure and straw (470 kg chicken manure + wheat straw). The average N-NH_3 production was 0.32 kg $N \cdot m^{-3}$.
- Each batch of the composting process lasts 44 days.
- 80% of the TAN emissions in the composting unit are recovered in the form of $(NH_4)_2SO_4$.
- The maximum recovery rate is 1.9 g TAN $m^{-2} \cdot day^{-1}$.
- The cost of the closed aerobic composter (7,767 €) was excluded from the analysis.
- The costs of the modifications made to the standard closed aerobic composter are itemized in Table S5, and account for 13,595 €.
- 7.7 m^2 of membrane has been used at a cost of 156.25 $€ \cdot m^{-2}$ (market price in 2020). A replacement of 20% per year is considered.
- The annualised costs of the equipment are calculated using a lifespan of 10 years and an interest rate of 8% [97].

- The energy consumption is estimated at 15.7 kWh day^{-1}.
- It is estimated that the compost produced is sold at 20 € $tonne^{-1}$ (average market price [1]).

Table S5. Estimated costs for the external compartment and modifications made to the standard closed aerobic composter in system S2.

Equipment	Cost (€)
PLC control	700
HMI screen	345
Acid pump	610
Prototype fan	450
Gas detectors	1,950
Temperature and pH probes	1,250
Flow probe	350
Potentiometer for controlling flowrate	350
Acid tank (150 L)	200
Structure	1,350
Piping	1,222
Electric board	2,135
Membranes mounting steel mounting	450
Composter fan	1,000
Temperature probe	30
Membranes	1,203
Total	13,595 €

Table S6. Summary of capital expenses, operating expenses and operating revenues for a closed aerobic composting system connected to an external compartment with the NH_3 capture system based on GPM technology.

Capital Expenses		
	Initial Investment (€)	**Annualized Costs: 8% interest, 10-year life (€/year)**
Nitrogen recovery prototype	13,595	2,026
Operational Expenses		
		Annual costs (€/year)
Membranes replacement (20%)	-	241
Chemicals (H_2SO_4)	-	10
Power (ΣkWh)	-	626
Total operational annual costs	-	877
Total annualized cost		2,903
Revenue (€/year)		
Sale of compost		38
Recovered nitrogen: 7.83 kg N/year (€ 2.36/kg N)		19
Net annual cost		2,846