CARBON FOOTPRINT EVALUATION OF BIOFERTILIZERS

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ABSTRACT

The prevailing large-scale use of chemical fertilizers has been affecting environmental degradation. A broken nutrient cycle has caused problems worldwide, which are related to the question of how to feed 9 billion people by 2050 while limiting human operations within the planetary boundaries. Indispensable nutrients, phosphorus (P) and nitrogen (N), often leak because of human activities, such as food production. Efficient nutrient recycling can alleviate the problem. This study focuses on biofertilizers as a solution for the problem of a broken nutrient cycle. The study quantified the environmental benefits of using biofertilizers by calculating the carbon footprints of P and N in organic fertilizers by using the life cycle assessment (LCA) method on an existing biogas plant. The emissions from common production processes are allocated between products and co-products. However, whether a side flow is regarded as a co-product or waste is sometimes unclear. According to ISO 14040 and the greenhouse gas (GHG) protocol, if a substance does not have a value or the holder intends to dispose it, it can be regarded as waste. Allocation of emission can be done according to parameters such as energy content, mass, or monetary value. The composted digestate was considered valuable; the allocation between biogas and nutrients was conducted according to the value of biogas and recycled fertilizers. The calculated carbon footprints were 0.8 $kg_{CO2,eq.}$/kg for N and 1.8 $kg_{CO2,eq.}$/kg for P, whereas the carbon footprints for mineral fertilizers were 1.9–7.8 $kgCO_{2,eq.}$/kg for N and 2.3–4.5 $kg_{CO2,eq.}$/kg for P. The reduction of GHG emission in organic fertilizer production in comparison with the emission in mineral fertilizer production was on average 78% for N and 41% for P. On the other hand, inclusion of N_2O and CH_4 emissions from composting increases the carbon footprints of nitrogen and phosphorus but there is high uncertainty included with these emissions. The value of nutrients in the biofertilizers is also uncertain but the interest towards using of them is increasing in Finland.
Keywords: anaerobic digestion, biofertilizer, biogas, carbon footprint, compost, digestate.

1 INTRODUCTION

The use of fertilizer on arable land has increased 60% during the past 50 years, and the challenge related to availability of fertilizers by 2050 is crucial since fertilizers ultimately play a key role in feeding the increasing population [1, 2]. Increased use of fertilizers has led to soil quality and environmental degradation, biodiversity loss eutrophication, and heavy metal pollution [3–5].

Phosphorus (P) and nitrogen (N) are among the key fertilizers used globally. Phosphorus is a crucial element for all living organisms and it has been termed 'life's bottleneck' [6]. The exploitable reserves of phosphate rock are continuously depleting because of the excessive use of phosphorus as fertilizers in agriculture and raw materials in some industries [7]. It is predicted that the available accessible reserves of clean phosphate rock would be diminished in the next 50 years unless some intensive measures are taken [8]. On the other hand, the growing demand for the N fertilizers has been primarily fulfilled by industrial fixation of atmospheric nitrogen (N_2) to ammonia (NH_3) via the Haber–Bosch process [9], which requires extensive amounts of energy.

Phosphorus and nitrogen are discharged across environmental media during food production or are wasted instead of being used for plant nutrition. The total losses to water and landfill are estimated to account for 30%–35% of the annual usage of phosphorus

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fertilizers [2]. This excessive use of nutrients and leakages have led to increasing competition for critical resources such as phosphorus reserves [10]. Furthermore, the excessive conversion of nitrogen into its reactive forms in fertilizers has resulted in a heavy transgression of the planetary boundary for the biological nitrogen flow [5]. This broken nutrient cycle is a mounting challenge for the whole world.

Nutrient recycling can be part of the solution among waste prevention and changes in diets. The biodegradable side flows can be valorized into biofertilizers that can promote a healthy nutrient cycle when used appropriately. While promoting the nutrient cycle, the production of biofertilizers should not produce more GHGs than the production of traditional mineral fertilizers. To estimate how they compare with traditional mineral fertilizers, the carbon footprint of phosphorus and nitrogen present in organic fertilizers were calculated and compared with those of mineral fertilizers.

2 METHODOLOGY

2.1 Carbon footprint calculation

Carbon footprint calculation was conducted by the life cycle assessment (LCA) methodology. The general description of the LCA method, the procedural steps involved, and guidelines are provided in standards ISO 14040 and ISO 14044 [11,12]. The main steps in LCA are goal and scope definition, inventory analysis, impact assessment, and interpretation of the assessment results. The carbon footprint calculation is more widely elaborated in Standard ISO 14067 [13], which also includes the above four steps of LCA.

In the goal and scope definition step, the system boundary and functional unit are defined. The system boundary includes the processes of the product system under study. ISO 14040 demands that the system boundary is transparent in order to ensure accurate interpretation of the results. Following from the goal of the study, the functional unit is 1 kg of nutrient and carbon footprint is calculated for nitrogen and phosphorus included in a compost product. An assumption of a zero burden condition on the incoming biodegradable waste was assumed. This means that the incoming waste does not have burden related to the production and use phases of materials. [14–16].

2.2 System boundary

The system boundary presented in Fig. 1 is defined according to the aim of calculating carbon footprint of nutrients in compost and it includes processes that are either common for biogas and digestate or related to the composting plant. The system boundary of the case facility includes energy consumption of the composting and biogas plants, transportation of feedstock and products. In addition, the electricity consumption of the wastewater treatment plant is included. The biogas upgrading and reject incineration are outside the system boundary because they are not related to compost production. The biogas upgrading process is only related to the produced biogas and the emissions are allocated to the biogas and compost from those processes, which are common for both. The system boundary and processes within the system boundary and those excluded from the system boundary are presented in Fig. 1. The emissions from the processes included within the system boundary are allocated to the produced biogas and the main fertilizers included in the compost.

The case facility consists of a biogas plant and a composting plant. Table 1 shows the data collected from year 2016. The main feedstocks to the biogas plant are biowaste and sewage

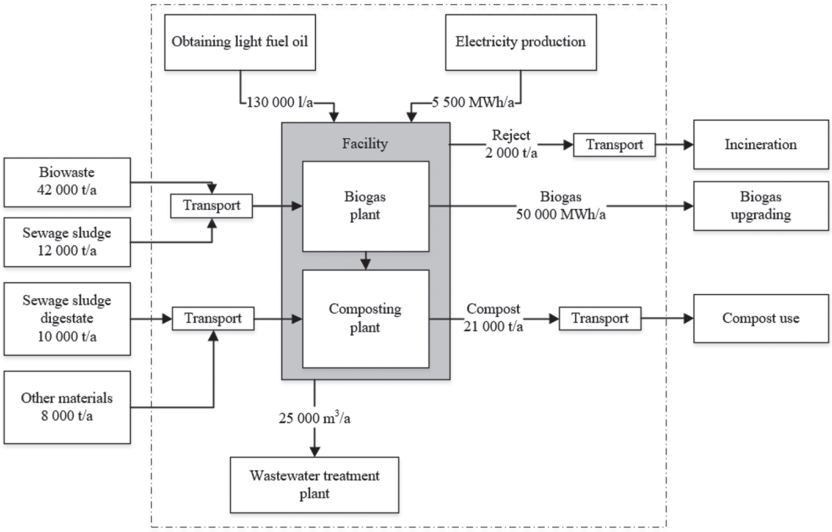

Figure 1: System boundary of the study.

Table 1: Material input and output of biogas plant and composting plant.

To biogas plant		
Biowaste <80 mm	14 000	t/a
Sewage sludge	7 300	t/a
Total	21 300	t/a
Directly to the composting plant (without entering biogas plant)		
Biowaste >80 mm	26 000	t/a
Garden waste (leaves)	3 700	t/a
Sewage sludge digestate (coming from outside facility)	12 000	t/a
Wood chips out of branches	2 100	t/a
Wood chips out of stumps and offcuts	1 800	t/a
Silicate gel slurry	3 000	t/a
Total	48 600	t/a
Output from facility		
Compost	20 900	t/a
Reject	2 800	t/a
Rain water from yard to wastewater treatment plant	17 000	m^3/a
Process water to wastewater treatment plant	7 500	m^3/a

sludge, as shown in the table. The biowaste comes from two locations and it is separated to a fraction that goes to biogas plant (<80 mm) and one that goes directly to the composting plant (>80 mm). The digestate from the biogas plant as well as other materials from outside the facility, such as sewage sludge digestate from other facilities, are directed to the composting plant. The produced biogas is upgraded and injected into the natural gas grid. The wastewater and rainwater collected from the facility are directed to a municipal wastewater treatment plant. The produced compost is used as a fertilizer in agriculture. The moisture content of the produced compost is 33% and it contains 1% of soluble nitrogen and 1.8% phosphorus, calculated as a percentage of the dry matter. Along with the compost, 140 t/a of soluble nitrogen and 250 t/a phosphorus exit the facility.

2.3 Energy balance and emission factors

The facility including the biogas plant and composting plant consumes electricity and light fuel oil. The electricity is supplied by two sources, power plant 1 and power plant 2, having different emission factors, as presented in Table 2. The wastewater treatment plant consumes 0.76 kWh/m^3 electricity, produced at power plant 2 [17]. Light fuel oil is used by the front-end loader and in the processes at the facility. The density of the light fuel oil is 0.84 kg/l [18] and the heating value is 43 MJ/kg [19]. The GHG emissions from the light fuel oil originate from its production and use; the emission factors are presented in Table 4.

The biowaste is transported from location 1 by semi-trailer trucks of a capacity of 25 t and from location 2 by heavy delivery lorries with a capacity of 15 t. [20] The transport vehicles are assumed to be loaded to full capacity when delivering the material and empty on return. The one-way distances are listed in Table 3 and the emission factors are given in Table 4.

The composting process is closed tunnel composting system with odor control consisting of cooling, biological scrubber and biofilter. The forced aeration is used to ensure that the composting process remains aerobic at tall times but there could also be N_2O and CH_4 emissions even though these emissions are not measured at the facility from the off-gases. To estimate the impact of these emissions to the carbon footprint; the N_2O emission was assumed as 0.7% of input N [24] and CH_4 emissions as 0.75 kg/t input material [25].

2.4 Allocation

In the case that the product system includes more than one output across the system boundary, the issue of allocation needs to be considered. In LCA, allocation means dividing the input or output flows of processes between the products and co-products, while allocation is not done for waste [13]. According to the standards ISO 14040, ISO 14044, and ISO 14067, the side flow can be considered waste when the holder intents or is required to dispose it

Table 2: The electricity and light fuel oil demand of facility and produced biogas.

Electricity	Power plant 1	3 300	MWh/a
	Power plant 2	2 200	MWh/a
Light fuel oil use	Process	60 000	l/a
	Front end loader	70 000	l/a
Biogas		42 000	MWh/a

Table 3: Transport distances of inputs and outputs.

Material	One-way distance (km)
Input	
Biowaste, location 1 (29 000 t/a)	100
Biowaste, location 2 (11 000 t/a)	10
Sewage sludge	14
Garden waste (leaves)	10
Sewage sludge digestate (outside facility)	20
Wood chips out of branches	10
Wood chips out of stumps and offcuts	10
Silicate gel slurry	70
Output	
Reject	80
Compost	42

Table 4: GHG emission factors of electricity, light fuel oil and transport [20–23].

Electricity	Power plant 1	70	$g_{CO2,eq.}$/MJ
	Power plant 2	45	$g_{CO2,eq.}$/MJ
Light fuel oil	Obtaining	449	$g_{CO2,eq.}$/kg
	Use	74	$g_{CO2,eq.}$/MJ
Transport	Semi-trailer truck	754	$g_{CO2,eq.}$/km
	Large delivery lorry	409	$g_{CO2,eq.}$/km

[11–13]. In addition, according to the ISO standards and GHG protocol [26], the allocation should be avoided, if possible, by dividing the common processes to sub-processes, using the system expansion or substitution method or by changing the functional unit to cover the co-products.

In case of biogas production, dividing the common processes to sub-processes or redefining the functional unit is not possible because the biogas and co-product digestate are generated from the same process. Allocation can be done, for example, on the basis of the physical or economic characteristics of the products, such as energy content, mass, or monetary value. ISO 14040, ISO 14044, and the GHG protocol promote, when allocation is not avoidable, the allocation based on physical relationship or using other relationships such as economic value; by contrast, Directive 2009/28/EC demands allocation to be done on the basis of energy content [27].

Calculation of the carbon footprint for nitrogen and phosphorus present in the compost requires that the emissions of the facility are allocated between nitrogen, phosphorus, and produced biogas. In this case, the energy content-based allocation is not suitable because the compost is not used in energy production and the heating value of the wet compost is very low. Mass-based allocation is also not suitable because the mass of compost is far greater than that of the produced biogas, which is used not as material but as an energy carrier. Therefore, the economic value-based allocation was selected; the used values suggested by Kahiluoto and Kuisma [28], which are listed in Table 5, are approximately half of the values of nitrogen and phosphorus in mineral fertilizers, which are presented in Table 6. However, it should be borne in mind that the value of compost for the producer might also be significantly lower. In some instances, in Finland, the final user can obtain the compost free or the producer of compost is even paying to get the compost to further treatment.

3 RESULTS AND DISCUSSION

3.1 GHG emissions

The energy consumption of the biogas plant and composting plant as well as transport of the materials produce GHG emission equal to 1.9 $kt_{CO2,eq.}$/a, Table 7. In addition the gaseous emissions of composting process amount to 1.9 $kt_{CO2,eq.}$/a but these emissions were not measured at the facility.

3.2 Carbon footprints

The GHG emissions were allocated according to the value of the produced biogas as well as nitrogen and phosphorus in the compost. The economic value of biogas is considerably

Table 5: Values used for the produced biogas and fertilizers included in the compost [28].

Product	Value
Soluble nitrogen	0.66 €/kg
Phosphorus	1.5 €/kg
Biogas	25 €/MWh

Table 6: Values of mineral fertilizers [29–31].

Producer / product	€/kg N	€/kg P
YaraMila NK2 650 kg	2.3	
YaraMila NK2 1200 kg	2.5	
YaraMila NK1 650 kg	1.9	
YaraBela salpetre	1.4	
Agro phosphorus 12 – 23 +Mg + S (500 kg)		5.3
Agro phosphorus 12 – 23 +Mg + S (pallet packed)		2.8
Belor agro Ltd.	0.93	1.98
Cemagro Ltd.	0.97	1.91
Yara Finland Ltd.	1.26	1.8
Average	1.6	2.8

Table 7: Annual GHG emissions of facility including anaerobic digestion, composting and transport of materials.

	GHG emissions	Share
	$kg_{CO2,eq.}$/a	%
Electricity used at the facility	1 200 000	31%
Electricity use of waste water treatment	3 000	0.1%
Light fuel oil	390 000	10%
Transport of inputs	240 000	6%
Transport of outputs	73 000	2%
Composting N_2O and CH_4 emissions	1 900 000	50%
Total	3 800 000	

greater than those of nitrogen and phosphorus; therefore, the majority of the emissions are allocated to the produced biogas (Table 8). This is the case even though the used values for nitrogen and phosphorus were relatively high and in reality, the values could be lower. The mass and the value of phosphorus exiting the facility are greater than those of nitrogen, which results in the allocation of a greater share of GHG emissions to phosphorus. Moreover, because the value of phosphorus is more than two times that of nitrogen, the resulting emission factor of phosphorus is more than two times that of nitrogen.

The carbon footprints of mineral nitrogen and phosphorus are summarized in Table 9 to compare them to the values calculated in this study; the table shows that on average the carbon footprint of mineral nitrogen is 3.7 $kgCO_{2,eq.}$/kg and mineral phosphorus is 3.1 $kg_{CO2,eq.}$/kg. The calculated carbon footprint (Table 8) of nitrogen is 57%–90% lower (on average 78%) and phosphorus is 26%–59% lower (on average 41%) than the corresponding carbon footprints in mineral fertilizers. When the N_2O and CH_4 emissions from composting process are included, the calculated carbon footprint of nitrogen is on average 56% lower but the calculated carbon footprint of mineral phosphorus is on average 19% greater.

The values of nitrogen and phosphorus are difficult to obtain; this uncertainty directly affects the calculation of the carbon footprint. The value of biogas can also vary based on whether the producer of the biogas upgrades the biogas and sells it in fueling stations

Table 8: Values of biogas and nitrogen and phosphorus, allocated GHG emissions, and carbon footprints of nitrogen and phosphorus (values in brackets indicate results including N_2O and CH_4 emissions from composting process).

	Value	Share	GHG emission	Carbon footprint
	€/a	%	$kg_{CO2,eq.}$/a	$kg_{CO2,eq.}$/kg
Biogas	1 100 000	70	1 300 000	–
Nitrogen	92 000	6	110 000	0.81 (1.6)
Phosphorus	380 000	24	460 000	1.8 (3.7)
Total	1 572 000	100	1 870 000	

Table 9: Carbon footprints of mineral nitrogen and phosphorus.

Nitrogen	$kg_{CO2,eq.}$/kg N	
YaraBela Extran 33.5	3.7	[32]
YaraBela Extran 27	3.9	[32]
YaraVera	3.3	[32]
YaraUAN	3.5	[32]
YaraLiva	4.2	[32]
YaraMila (NPK)	5.3	[32]
Yara Glomfjord	3	[33]
Yara Porsgrunn	2.8	[33]
Yara Siilinjärvi	3.1	[33]
Yara Uusikaupunki	3.3	[33]
Yara Rostock	3.2	[33]
Yara Sluiskil	2.5	[33]
EU BAT	3.6	[33]
EU average NH_3 plants	7.8	[33]
Ammonium nitrate	3.5	[34]
Ammonia	1.9	[35]
Phosphorus	$kg_{CO2,eq}$/ kg P	
Phosphorus	2.7	[36]
Triple superphosphate (TSP)	2.8	[37]
Monoammonium phosphate	4.5	[37]
TSP Europe average	2.5	[35]

themselves or whether it is sold before upgrading. The value of soluble nitrogen was changed from 0 €/kg to 1.4 €/kg, which is close to the nitrogen value in mineral fertilizer (Table 2) and the value of phosphorus was calculated using the ratio of phosphorus and soluble nitrogen values from Table 1; the value thus obtained is 2.3. The value of biogas at the fueling station was used as the estimation of maximum obtainable value for biogas, which is approximately 80 €/MWh in Finland in 2018. Figure 2 shows that if the prize of nitrogen and phosphorus would get closer to the prizes of nitrogen and phosphorus in mineral fertilizer, the carbon footprint would be 2.9 $kg_{CO2,eq.}$/kg for phosphorus and 1.3 $kg_{CO2,eq.}$/kg for nitrogen, when using 25 €/MWh as biogas prize. If the prize would be 80 €/MWh the carbon footprints would be 53% lower.

4 CONCLUSIONS

The carbon footprints of nitrogen and phosphorus present in the compost from a facility that treats mainly sewage sludge and biowaste through anaerobic digestion and composting were calculated by allocating the GHG emissions on the basis of the economic value of the products. The GHG emissions were mainly allocated to the produced biogas because the economic value of this product far exceeds those of nitrogen and phosphorus included in the compost. The calculated carbon footprints were 0.8 $kg_{CO2,eq.}$/kg for nitrogen and 1.8 $kg_{CO2,eq.}$/kg for

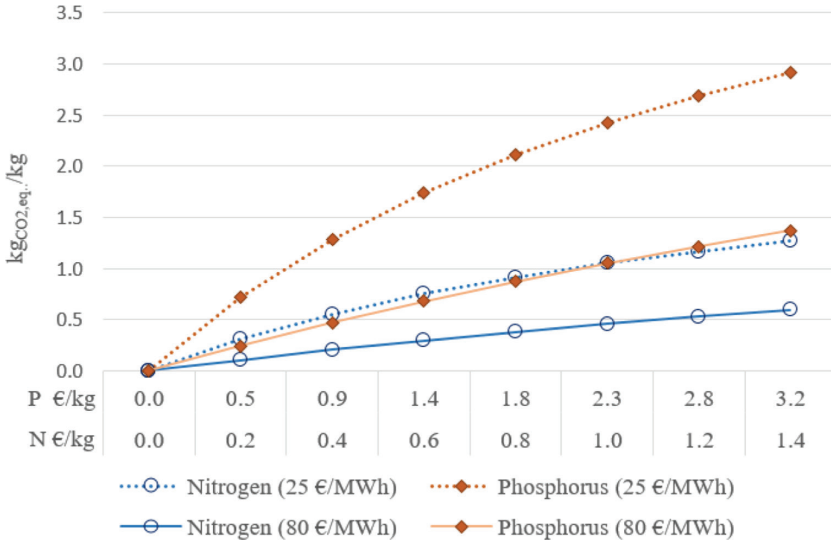

Figure 2: Carbon footprint of nitrogen and phosphorus included in a compost product in relation to the values of nitrogen and phosphorus, using 25 €/MWh or 80 €/MWh as biogas value.

phosphorus. The calculated carbon footprint of nitrogen was 57%–90% lower than that in mineral nitrogen and the carbon footprint of phosphorus was 26%–59% lower than that in mineral phosphorus. If values of nitrogen and phosphorus in compost are equal to those in mineral fertilizers, half of the emissions generated would be allocated to fertilizers, resulting in carbon footprints of 1.3 $kg_{CO2,eq.}$/kg for nitrogen and 2.9 $kg_{CO2,eq.}$/kg for phosphorus. However, also in this case, the carbon footprints of the nutrients included in the compost would be on average lower than those of mineral fertilizers. Including the NH_3 and CH_4 emissions of composting process would increase the carbon footprint of nitrogen and phosphorus significantly, but there is uncertainty in these emissions since they were not measured at the facility. Furthermore, presently the value to the producer of some biofertilizers such as compost, which includes sewage sludge as feedstock compost, is low in Finland but the interest towards biofertilizers is increasing.

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