Abstract

An increasing amount of plastics and microplastics enters terrestrial and aquatic ecosystems, causing concern regarding potential long-term effects on the carrying capacity of ecosystems and human health. One source of plastics and microplastics is from plastic residue in bio-fertilizers produced from organic waste and spread on agricultural land.

This study estimated the amount and reduction potential of plastics and microplastics in bio-fertilizer produced by ”Greve Biogass” in their production facility ”Den Magiske Fabrikken” (DMF). An important assumption for this study is that the level of plastics entering DMF is correlated to the level of plastic residue in bio-fertilizer. Based on the estimates of the sensitivity throughout and across the sections in the process model, the amount of plastics ending up in the bio-fertilizer will be directly correlated to any changes upstream of DMF. The implementation of combined measures upstream and downstream of DMF has resulted in a significant reduction potential of plastics and microplastics in bio-fertilizer.

The quantification of the level of plastics entering DMF revealed that around 2000 tons of plastics entered the biogas facility in 2018 while it was estimated that the bio-fertilizer delivered to the market contained 4,47 tons (DM) of plastic residue > 4 mm.

Through the implementation of alternative waste bags, adapted to the collection practice of each supplier of organic household waste (OHW) and utilized in waste handling systems which enables aeration and ventilation during storage, the level of plastic residue from plastic waste bags can be reduced to near zero. Because the level of incorrectly sorted plastics in OHW variates from each supplier, this level can be reduced to a feasible minimum by adopting the collection practices and experiences from suppliers with the least levels. Thirdly, by imposing stricter demands on suppliers of commercial organic waste, pre-sorting among them, the level of plastic packaging can be reduced to a feasible minimum. Finally, for any remaining plastic residue in bio-fertilizer, post-treatment in the form of Fournier Rotary Press in combination with composting of its dry fraction resulted in a cumulative reduction potential of 92%.

Sammendrag

En økende mengde plast og mikroplast gjør sin inntreden i økosystemer til lands og til vanns. Dette fører til bekymringer for potensielle langtidsvirkninger for bæreevnen til økosystemene og folks helse. En kilde til plast og mikroplast kommer fra plastrester i biogjødsel som produseres fra organisk avfall og blir sprøytet på dyrket mark.

Denne studien har estimert et reduksjonspotensiale for plast og mikroplast i biogjødsel produsert av ”Greve Biogass” i deres produksjonsfasiteter ”Den Magiske Fabrikken” (DMF). En viktig antakelse for denne studien er at mengden plast som kommer inn til DMF er korrelert til mengden plast i biogjødsel. Basert på estimatet av sensitiviteten gjennom og på tvers av seksjonene i prosessmodellen er mengden plast i biogjødsel direkte korrelert til forandringer oppstrøms for DMF. En implementering av kombinerte tiltak oppstrøms og nedstrøms for DMF har resultert i et signifikant reduksjonspotensiale for plast og mikroplast i biogjødsel.

Kvantifisering av mengden plast har vist at rundt 2000 tonn plast ankom DMF i 2018, mens det ble estimert at biogjødsel levert til markedet inneholdt 4,47 tonn (TS) plastrester > 4 mm.

Gjennom en implementering av alternative avfallsposer, tilpasset innsamlingspraksisen for hver leverandør av matavfall og brukt i avfallssystem som tilrettelegger for lufting og ventilering under lagring, kan mengden plastrester fra plastposer bli reduser til nær null. Mengden usortert plast i matavfall varierer fra hver enkelt leverandør, men denne mengden er mulig å redusere til et minimalt nivå ved å ta i bruk innsamlingspraksisen og bruke erfaringene fra leverandørene som har minst mengde usortert plast i deres matavfall. For det tredje, ved å innføre strengere krav til leverandører av kommersielt matavfall, blandt annet førsortering av plast, kan mengden emballasjeplast bli redusert til et minimunsnivå. Som et siste tiltak kan gjenværende plastrester i biogjødselen fjernes gjennom etterbehandling i form av Fournier rotasjonspresser i kombinasjon med kompostering av tørrfraksjonen. Alle ovennenvte tiltak har blitt estimert til å ha et akkumulert reduksjonspotensiale av plastrester på 92%.

Abbreviations

CO_2	Cardon dioxide
COW	Commercial organic waste
DM	Dry matter
DMF	Den Magiske Fabrikken
ESAR	Advanced optical sorting facility
FO	Foreign objects
FRP	Fournier Rotary Press
FTIR	Fourier transform infrared spectroscopy
HDPE	High-density polyethylene
IØR	Indre Østfold Renovasjon
LAM	Liquid animal manure
LDPE	Low-density polyethylene
LOIW	Liquid organic industrial waste
MPP	Microplastic particles
MFA	Material flow analysis
MSW	Municipal solid waste
OHW	Organic household waste
OW	Organic waste
PBAT	Aliphatic-aromatic copolyester
PE	Polyethylene
PLA	Polylactic acid
PP	Polypropylene
RfD	Renovasjonsselskapet for Drammensregionen
RiG	Renovasjon i Grenland
RoAF	Romerike avfallsforedling
SR	Sensitivity ratio
SWMA	Swedish Waste Management Association
WW	Wet weight

Preface

This thesis comprises 30 ECTS credits and concludes my degree as a Civil Engineer. The thesis was written in cooperation with The Norwegian University for Science and Technology - Department of Energy and Process Engineering, The Technical University of Denmark - Department of Environmental Engineering, the solid waste management company Vesar and the biogas producer Greve Biogass.

Numerous people were involved and has contributed to my work both preceding and concluding this thesis. Worth to mention are my supervisors, Helge Brattebø (NTNU), Sigrun Jahren (NTNU), and Anders Damgaard (DTU). From Vesar and Greve Biogass, Terje Kirkeng, Mariann Hegg and many others has provided excellent communication and transfer of important data. The work preceding this thesis involved several interviews and enterprise visits with key actors and support actors in the solid waste management sector. I found the networking and insights into the solid waste management sector quite amusing because of the ambition and united effort to deal with the current issues of plastic and microplastic pollution.

The written language for this thesis is English, however, the non-English decimal separator, “decimal comma”, has been utilized instead of the English decimal separator, “decimal point”.

As of 2020, changes and fusions has occurred within the municipal and provincial sector in Norway. This has resulted in many of the municipalities and provinces mentioned in this paper to be outdated or renamed.

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1 Introduction

In recent years and along with other nations, the Norwegian government included the UN's Sustainable Development Goals in its policies. These are policies aimed to reduce CO_2 emissions and increase clean and renewable infrastructure and technologies. Simultaneously, in the wake of the increased knowledge surrounding climate change and environmental challenges, increased public pressure and for the benefit of the industry itself, an increasing share of the Norwegian industrial sector is transitioning toward a circular economy.

Over the last decades the solid waste management sector has replaced the model of disposal (i.e., landfilling) with the policy of waste-to-energy. Instead of landfilling, an increased share of waste is either being energy recycled or material recycled. Incineration is a form of energy recycling where waste is transformed to heat and electricity while anaerobic fermentation is a form of material recycling where organic waste is transformed to biogas and bio-fertilizer.

"Greve Biogass" is one of those companies built on the model of material recycling and circular economy. Through the processing of organic waste from various sources, their facility produces biogas and bio-fertilizer. While supplying an increasing share of the transport sector with environmentally friendly biogas, it also supplies the agricultural sector with bio-fertilizers.

The all-encompassing issue that all biogas producers are facing today is the issue of plastic residue in the bio-fertilizer. Expensive pre-treatment technologies are installed to reduce the level of plastics entering the bioreactors. However, no sufficient treatment technology exists which can completely solve the issue of plastic residue in bio-fertilizer. For this reason, the plastics that pass through pre-treatment persist through the whole process, ending up in the fields of the farmers. Organic household waste (OHW), one of the main constituents of organic waste delivered to "Greve Biogass", is collected in plastic waste bags. Incorrectly sorted waste like plastics and other foreign objects constitutes a noteworthy percentage of the content in the plastic waste bags. Commercial organic waste (COW), an important constituent of organic waste delivered to "Greve Biogass", is often delivered entirely in its original plastic packaging from its suppliers. Because no pre-sorting exists to separate plastics and organic waste before the pre-treatment process starts, both types of material enter the same pre-treatment process.

In most cases the level of plastic residue and foreign objects in bio-fertilizer is below legally-defined threshold. Still, there is a quantifiable and visible amount of plastics in the bio-fertilizer. Compared to the density of sand, stone, and metals, all plastics are lightweight materials. Thus, one unit of plastic occupies a far larger area than one unit of the heavier materials with foreign objects. This has resulted in farmers imposing biogas companies with stricter demands. Unless visible amounts of plastics are reduced in bio-fertilizer, farmers will refuse to accept bio-fertilizer delivered by biogas companies. In conjunction with the farmer's demands, consumers have also voiced their concerns regarding bio-fertilizer produced from food waste. Farmers, mainly due to the increasing visual issues plastics bring, and consumers, due to the possible health issues associated with possible formation of microplastics in the food chain.

The main objective of this study is to map the origin of plastics entering bio-fertilizer and find the plastic residue reduction potential through the implementation of several measures. In essence, the research for this study further contributes to a deeper and overall understanding of the issue of plastic residue in bio-fertilizer. For all practical purposes, this study will mainly focus its efforts on “Den Magiske Fabrikken” (DMF), “Greve Biogass” anaerobic fermentation facility which is located outside Tønsberg, Norway.

The following tasks were performed to answer the objectives:

1. A literature study has been conducted on topics of relevance to this project, focusing on plastic and micro plastic residue in bio-fertilizer, anaerobic digestion, and solid waste management.

2. An upstream analysis was conducted to map and model the inflow of OHW to DMF and has served as a foundation for the Material Flow Analysis (MFA) conducted. The upstream analysis includes mass flows of both organic material and foreign objects in OHW, waste handling solutions for the individual collectors of OHW and transport transfer points.

3. The upstream analysis was used to analyze the current situation and to develop scenarios for future waste handling solutions through the utilization of alternative waste bags, tougher demands for suppliers of COW, reduction of incorrectly sorted plastics to a feasible minimum, and additional treatment technology. Different scenarios have been assessed and compared to the current situation to determine which scenario performs the best for plastic residue reduction in bio-fertilizer.

4. The main findings in this study have been discussed (i.e., level of performance for alternative waste bags and other initiatives for plastic residue reduction in bio-fertilizer). Based on the coherent knowledge gained in this study, this study has provided recommendations for optimal food waste management. Lastly, this study has recommended future work.

2 Literature

The contamination of the environment with microplastics, defined as plastic particles <5 mm, has emerged as a global challenge because it may pose risks to ecosystems and public health. Both aquatic and terrestrial ecosystems are being polluted from various sources, notably the tearing and wearing of car tires, synthetic clothing fibers from laundry, ship painting, and bio-fertilizers. Current research has so far had a predominant focus on aquatic ecosystems, whereas comparatively little is known about terrestrial ecosystems. Anthropogenic littering is a known cause of plastic pollution in terrestrial ecosystems, however, the knowledge surrounding the sources, pathways, and possible accumulation of plastic particles in terrestrial ecosystems is scarce. Terrestrial ecosystems in our case include gardens, public parks, and especially agricultural lands. For the latter case, two studies that will be presented in Subchapter 2.2 are helpful in providing a deeper understanding of the sources and entry of microplastics into the environment and agricultural land. However, it is important to grasp why the current fertilizer regulations are not compatible with current and future policies and how they are most likely contributing to the current issue of plastic residue in bio-fertilizer. Therefore, our literature study will first and foremost contain a presentation of the present fertilizer regulations and newer, more adapted fertilizer regulations.

2.1 Fertilizer regulations in Norway and Sweden

The Norwegian fertilizer regulations (i.e., “Regulations on fertilizers of organic origin”) have been the industry standard for the legally defined threshold of foreign objects in bio-fertilizer produced and applied in Norway. Published in 2003 and formed during the 1980s and 1990s under the supervision of the agricultural, environmental, and health department, the Norwegian fertilizer regulations have benefited the production and application of bio-fertilizer within the requirements of the nutritional, environmental, and health regulations. The current regulations state that the total content of plastics, glass, and metals > 4 mm can maximum constitute 0,5% in weight percent of dry matter basis of the bio-fertilizer (*Forskrift om gjødselvarer mv. Av organisk opphav—Lovdata*, 2019).

In conjunction with the waste-to-energy policy, an increased amount of organic waste from households and commercial sources is transformed to bio-fertilizer and, a noteworthy share of plastic residue is observed by producers and users of bio-fertilizer. Previously mentioned, plastics are lightweight materials, and are occupying a far larger volume and area compared to heavier elements. This has contributed to a review and potential improvement of the Norwegian fertilizer regulations more compatible and adapted to the current policies and issues.

The Swedish Waste Management Association (SWMA) established a new industry standard for bio-fertilizer, SPCR 120, more compatible with current policies and issues. This standard requires bio-fertilizer producers to comply with regulations stating that the 12-month mean value of plastics, glass, metals, and composite materials in bio-fertilizer > 2 mm cannot exceed 20 cm^2/kg while individual samples cannot exceed 40 cm^2/kg. The SWMA and SPCR 120 states that the mean value shall be at least halved by 2020, and the value for individual samples shall be significantly reduced (Avfall Sverige, 2016).

2.2 Complementary studies and publications

The following subchapter contains a presentation of four important studies complementary to our study. The first study presents various processing plants for organic waste in Germany, their various input and corresponding level of plastic residue in output. The second study presents a comparison of different biogas and bio-fertilizer plants in Norway, detailing our case, “Den Magiske Fabrikken”, its pre-treatment technology and level of plastic residue in substrate and bio-fertilizer. The third study compares the natural degradation of different plastics utilized in the collection and handling of organic household waste (OHW) in different environments. The last study presents the results for a specific type of post-treatment technology tested in “Den Magiske Fabrikken” and the analysis of its results performed as a precursor to this study.

2.2.1 Organic fertilizer as a vehicle for the entry of microplastic into the environment

A study conducted by Weithmann et al. (2018) investigated the potential of organic fertilizers from organic waste fermentation and composting as an entry path for micro plastic particles (MPPs) >1 mm into the environment. Particles were classified by size and identified by Fourier transform infrared spectroscopy (FTIR). All compost and bio-fertilizer samples from plants converting organic waste contained MPPs, except for Plant C used as reference. However, the amount varied significantly with the source and treatment of organic waste. Composts, bio-fertilizers, and a percolate-leachate from a wide variety of plants were examined and compared. From Weithmann et al. (2018), the findings were based on four different facilities.

Plant A is an aerobic composting plant, which receives 8000 tons/yr of OHW and 12000 tons/yr of green clippings. Its pre-treatment consists of sieving through 80 mm meshes followed by metal separation. Rejected material > 80 mm is manually sorted of foreign objects before being mechanically shredded and refed through the sieving. The temperature in the rotting container reached temperatures above 70°C. Plant A offers two types of certified compost, namely CP 8 and CP 15. After the rotting container, the compost is being matured in open piles for several months, followed by a final sieving through 8 and 15 mm meshes which produces the CP 8 and CP 15, respectively.

Plant B is an anaerobic fermentation plant, which receives mainly OHW with the addition of some green clippings and occasionally energy crops. The mixture, 11000 tons/yr of OHW and 3000 tons/yr of green clippings, is introduced directly into a nonstirred, discontinuous box fermentation system with operating temperatures between 40-45°C. No manual sorting or pre-treatment exists for Plant B as the mixture is fed directly to the bioreactors. After 28 days of fermentation, the digestate is sieved through a 20 mm mesh to remove foreign objects before it is processed into fertilizer and potting soil using an aerobic composting process. High quality compost, Digest A, is produced by letting the digestate be matured for 11 to 13 months followed by sieving through a 10 mm mesh. Low-quality compost, Digest B, is produced by letting the digestate be matured for 8 to 9 months, with no additional sieving. In addition, Plant B offers non-matured fertilizer, Digest C, and the pooled percolate, Digest D. No information was given in regards to post-treatment methods for the latter digests.

Plant C is an anaerobic energy crop bioreactor used as a reference. Energy crops include 3200 tons/yr of corn/grass silage and 200 tons/yr of ground wheat. Both the silage and ground wheat arrive in plastic encasings, however, the encasings are removed before the substrate is passed through the shredder and enters the bioreactor. The bioreactor have operating temperatures of 42-45°C.

In addition to the three plants, Weithmann et al. (2018) also examined the bio-fertilizer produced by a fourth plant, called Plant D, and the digestate from 10 additional agricultural biogas plants, plants E to N. Plant E to N are processing feeds such as dung/manure, sunflowers, waste from fruit processing, together with the regular energy crops. Plant D receives waste solely from commercial organic waste (COW), 16000 tons/yr, particularly waste from the local market, as well as waste from food and drink industries. No information was given regarding treatment methods for the organic waste passing through Plant D.

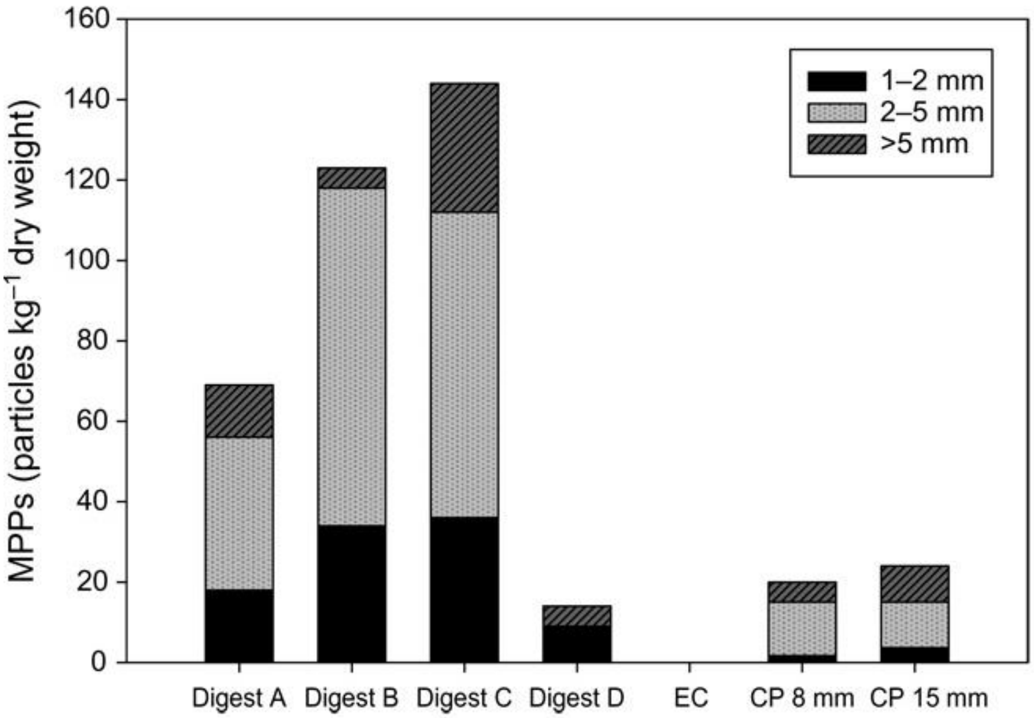
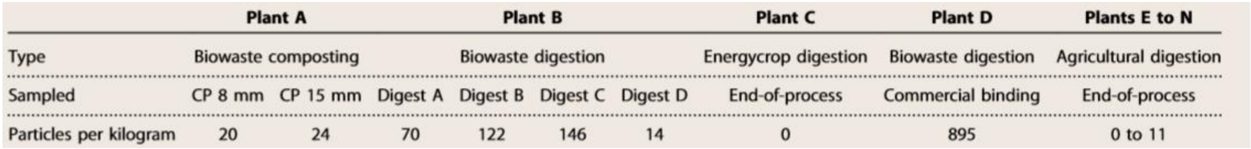
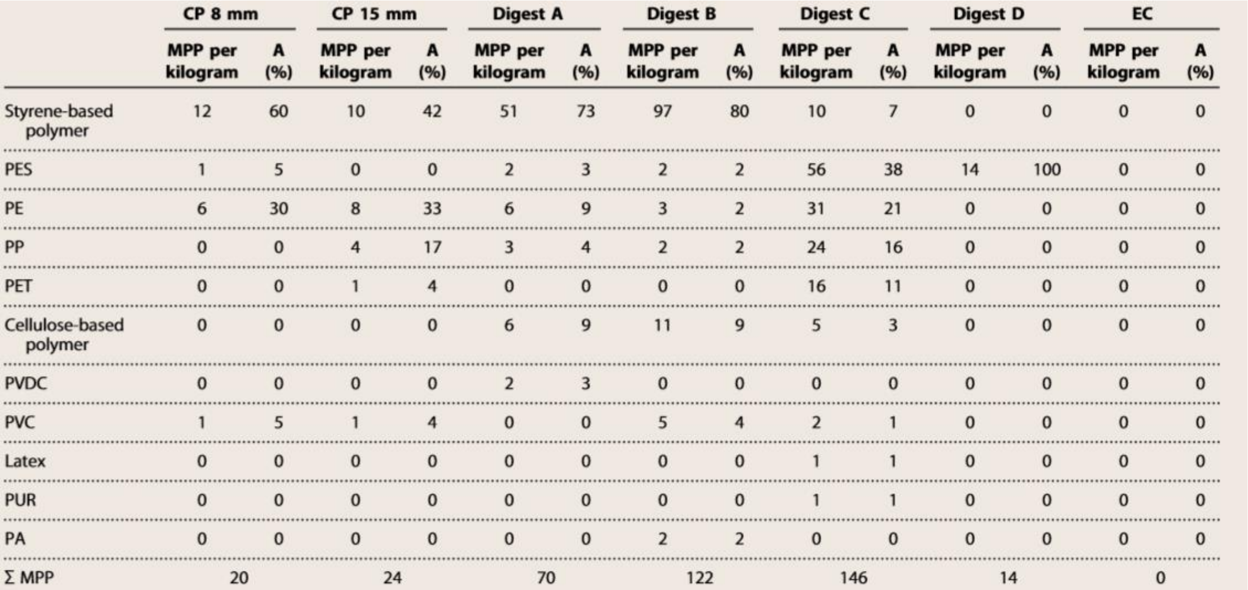


Figure 2.1: Level of MPPs in digests A/B/C/D from Plant B, anaerobic fermentation plant; EC from Plant C, energy crop bioreactor; CP 8 mm/15 mm from Plant A, aerobic composting plant (Weithmann et al., 2018).



	Plant A		Plant B				Plant C	Plant D	Plants E to N
Type	Biowaste composting		Biowaste digestion				Energycrop digestion	Biowaste digestion	Agricultural digestion
Sampled	CP 8 mm	CP 15 mm	Digest A	Digest B	Digest C	Digest D	End-of-process	Commercial binding	End-of-process
Particles per kilogram	20	24	70	122	146	14	0	895	0 to 11

Table 2.1: The total number of MPPs is shown as particles > 1 mm kg-1 of dry weight in compost and bio-fertilizer from the different plants (Weithmann et al., 2018).



	CP 8 mm		CP 15 mm		Digest A		Digest B		Digest C		Digest D		EC	
	MPP per kilogram	A (%)	MPP per kilogram	A (%)	MPP per kilogram	A (%)	MPP per kilogram	A (%)	MPP per kilogram	A (%)	MPP per kilogram	A (%)	MPP per kilogram	A (%)
Styrene-based polymer	12	60	10	42	51	73	97	80	10	7	0	0	0	0
PES	1	5	0	0	2	3	2	2	56	38	14	100	0	0
PE	6	30	8	33	6	9	3	2	31	21	0	0	0	0
PP	0	0	4	17	3	4	2	2	24	16	0	0	0	0
PET	0	0	1	4	0	0	0	0	16	11	0	0	0	0
Cellulose-based polymer	0	0	0	0	6	9	11	9	5	3	0	0	0	0
PVDC	0	0	0	0	2	3	0	0	0	0	0	0	0	0
PVC	1	5	1	4	0	0	5	4	2	1	0	0	0	0
Latex	0	0	0	0	0	0	0	0	1	1	0	0	0	0
PUR	0	0	0	0	0	0	0	0	1	1	0	0	0	0
PA	0	0	0	0	0	0	2	2	0	0	0	0	0	0
Σ MPP	20		24		70		122		146		14		0	

Table 2.2: Types of MPPs kg-1 of dry weight in the different composts and bio-fertilizers. “A” shows the proportion of each polymer in each product (Weithmann et al., 2018).

The results shown in Figure 2.1, Table 2.1, and Table 2.2 show huge variations in MPPs levels in compost and bio-fertilizers. In Plant C and E-N, where the input to the bioreactors is solely plant- and agricultural waste, the levels of MPPs are 0-11 particles per kilogram (p/kg). In Plant A producing CP 8 and CP 15, the levels of MPPs are 20 and 24 p/kg. Plant B has levels of MPPs ranging from 14 to 146 p/kg, were the percolate-leachate/pooled percolate and the non-matured fertilizer has the lowest and highest levels. Plant D showing the highest amount of MPPs in their bio-fertilizer, 895 p/kg.

This study increases our perspective regarding plastic residue in bio-fertilizer, because a wide variety of plants, treatment technologies, and organic waste are included. Plants with both pre- and post-treatment and/or plants with organic waste originating from mostly plant and agricultural waste, contains the least amount of plastic residue in compost and bio-fertilizer. Plants where organic waste undergoes the least treatment and/or plants that receive high amounts of OHW and COW contain the largest amount of plastic residue in their compost and bio-fertilizer.

2.2.2 Quality of substrate for biogas plants

In 2017, "Greve Biogass" conducted a study entitled "Kvalitet på substrat til biogassanlegg" which compared several biogas and bio-fertilizer facilities in Norway (Greve Biogass, 2017). The main aim of the study was to measure the quality of the substrate entering bioreactors. The study compared the respective facilities of Greve Biogass, Lindum, Ecopro, Romerike Biogassanlegg (EGE/RBA) and Frevar, which all convert organic waste to biogas and bio-fertilizer through anaerobic fermentation. Among measuring the quality of substrate entering bioreactors, important aspects such as quantifying the sources of organic waste and facility description were included in the study. Due to the classified nature of the report, only data regarding the results from "Greve Biogass", herby referred to as Den Magiske fabrikken (DMF), were available for this study.

DMF received 110401 tons of organic waste in 2017, with a 60% share from liquid animal manure and liquid organic industrial waste, which is assumed free of foreign objects. The pre-treatment in DMF consists of several steps. OHW and COW are fed to a mechanical shredder with a crane from the receiving bunker. After being processed by the mechanical shredder, the organic waste enters a pulper where dilution water is added. From the pulper, organic waste enters a separator with a 6x2 mm mesh and additional dilution water is added. The reject from the separator is dewatered through a strain presser before being transported to a reject container. The accept from the separator is pumped to a hydro cyclone where heavier foreign objects are removed before being transported to the buffer tank. After the buffer tank, all organic waste goes through sanitation, 70°C for 30 minutes, before entering the bioreactor.

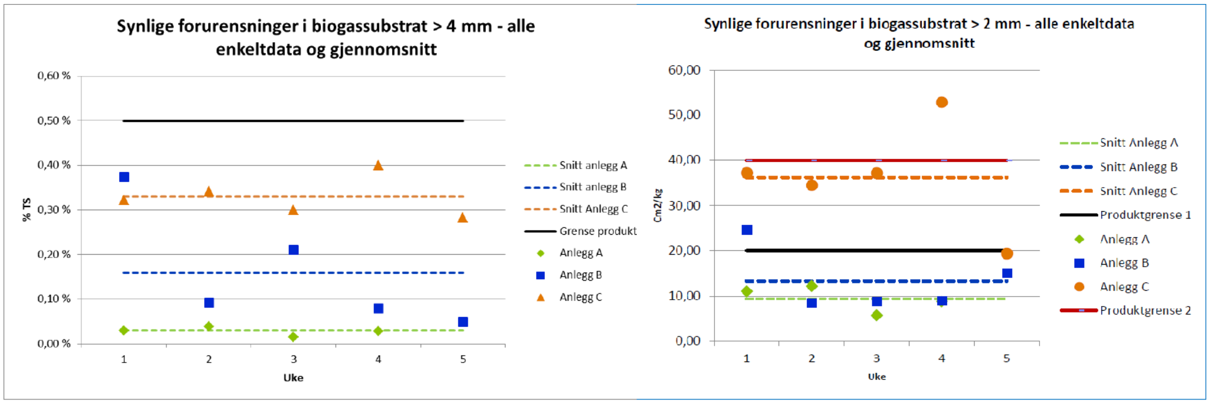


Figure 2.2: Foreign objects > 4 mm in % DM, and foreign objects > 2 mm in cm^2/kg, in substrate (Greve Biogass, 2017).

From the resulting Figure 2.2, DMF is depicted as "Anlegg A" in a light green color. Analysis of substrate in DMF shows that foreign objects > 4 mm comprise 0,03% of the DM in substrate, of which plastics comprising 78,3% of these foreign objects. Parallel analysis using the SPCR 120 method revealed foreign objects > 2 mm covering 9,4 cm^2/kg of substrate. We can observe that level of foreign objects in % DM and cm^2/kg are well within legally-defined limits, depicted as "Grense produkt" and "Produktgrense 1 and 2".

Parallel to the substrate analysis, a single sampled analysis of the bio-fertilizer exiting the bioreactor was conducted at DMF. Level of foreign objects > 4 mm comprised 0,09% of DM, of which plastics comprising 96%, and foreign objects > 2 mm covered 8,5 cm^2/kg–both within legally-defined limits, as stated in Chapter 2.1.

COW, which constitutes a noteworthy share of the organic waste delivered to DMF, was also analyzed in Greve's study. The mean average of four independent pick-analyses of COW originating from grocery stores, offices, and the like showed the level of foreign objects to be as high as 17%, of which plastics constituted 11,5% of COW.

The results *indicate* that "Greve Biogass" has the best pre-treatment method as level of plastic residue in substrate are the lowest compared to the other facilities, however, comparing the level of foreign objects in "Anlegg A" with "Anlegg B" from the SPCR 120 method, the difference in the average results are minor. Given the known composition of organic waste entering DMF and the unknown composition of organic waste entering "Anlegg B" the results are inconclusive, as both facilities should have received the same composition of organic waste for the results to be decisive.

2.2.3 Environmental deterioration of different plastic waste bags in different environments

A study by Napper & Thompson (2019) conducted in Britain, examined biodegradable, oxo-biodegradable, compostable, and high-density polyethylene (HDPE) carrier bags materials over 3 years. These materials were exposed to three natural environments, open-air, buried in soil, and submerged in seawater, as well as in controlled laboratory conditions. Measuring the tensile strength and surface area changes were the main objectives of this study.

Each carrier bag type was cut into strips (15x25 mm) from the main body of the carrier bag. A strip of each carrier bag type was then placed into a pouch made of HDPE mesh (1x1 mm), allowing exposure to external environments and sewn securely using nylon fishing twine, still allowing the carrier bag samples to move relatively freely. Each pouch had the measure of 150x200 mm and provided five equally spaced separated compartments.
The buried samples were situated at the University of Plymouth's Skardon Garden and were buried to a depth of approximately 0,25 m in soil that freely drain and is slightly acidic.
The samples that were exposed in open-air were also situated in Skardon Garden and were placed on a south-facing wall exposed to temperatures between 1,5-21,5 ˚C.
Samples placed in the marine environment were submerged on a beam at Queen Anne's Battery Marina at a depth of approximately 1 m and were exposed to temperatures of 8,8-18,8 ˚C.
Control samples were placed in a blacked-out box in a laboratory at the University of Plymouth, in room temperatures.

All samples were deployed on the 10th of July 2015 and there were three subsequent sampling dates after 9, 18, and 27 months. Additionally, whole carrier bags of each material were also deployed in polypropylene mesh in each environment at the same time and used for visual inspection over 3 years.

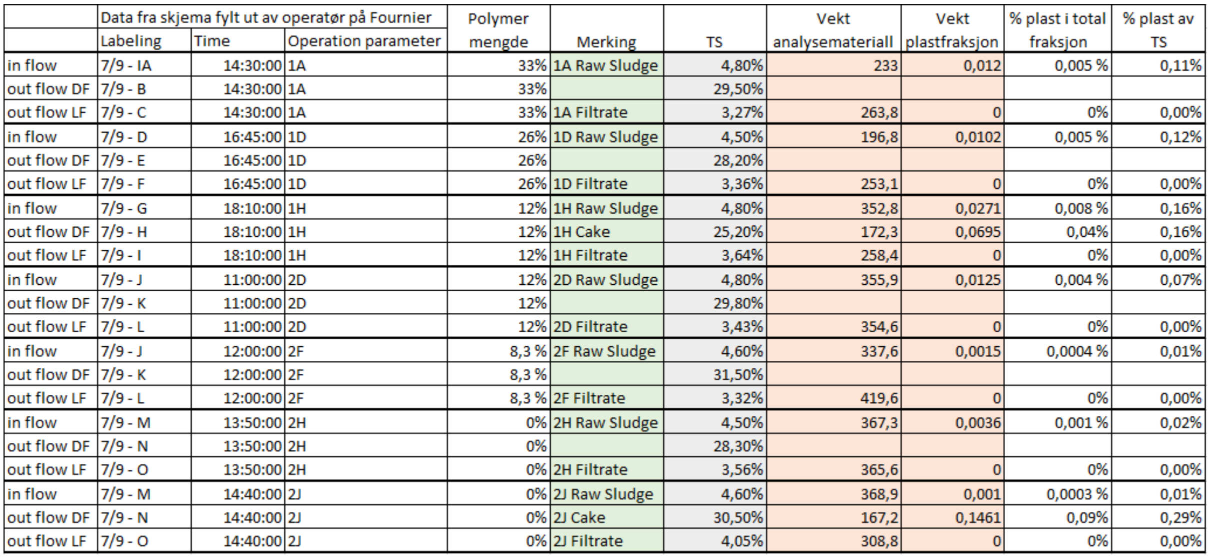
For strips of HDPE in both the control and soil environment, no surface area loss was measurable over the 27 months.
Within the marine environment, a microbial biofilm was visible on the surface of all carrier bag strips after 1-month. However, the compostable bag samples, including whole bags, were no longer visible by the first sampling date of 9 months.
After 9 months, in the open-air environment, all carrier bag types were too brittle to test and had or were disintegrating into pieces. The whole bags were also found to have disintegrated into microplastic pieces.

The compostable carrier bag and the deterioration of the samples are of interest in this study because decision makers in the biogas industry is considering this type of carrier bag as a feasible standard and replacement for PE waste bags. Hence, its degradation behavior is important to consider. Napper and Thompson’s study indicate total biodegradation of the compostable bags in marine environments after 9 months, total disintegration when exposed to open-air environments after 9 months and no surface loss in soil over 27 months.

2.2.4 Post treatment technology – Fournier Rotary Press

The following text contains work conducted by Fagerheim (2019) preceding this study.
In September 2018, “Greve Biogass” conducted pilot tests with the Fournier Rotary Press (FRP), 1 mm mesh size, to determine the best available performance of the FRP. This implies its effectiveness in reducing plastic residue with the least/acceptable loss of organic material. The FRP is a *rotary* press were the liquid bio-fertilizer is separated into a liquid and solid fraction. In theory the FRP will reduce the level of foreign objects in the liquid fraction while increasing the level of foreign objects in the solid fraction. The inflow is called “Raw Sludge”, while the two outflows, one liquid and one solid, are called “Filtrate” and “Cake”, respectively.

Average values from *all* tests showed 4,7% DM in “Raw Sludge”, 3,58% DM in “Filtrate” and 29,1% DM in “Cake”. Operational parameters desired by DMF resulted in 3,9% DM in “Filtrate” and 30,7% DM in “Cake”, while the capture rate was reduced from 22,1% to 15,0%. A reduction in capture rate means more bio-fertilizer available to farmers (Fournier Industries, 2018). The analysis of plastic residue content in all flows was performed in DMFs labs as well as in external labs.



	Data fra skjema fylt ut av operatør på Fournier			Polymer mengde	Merking	TS	Vekt analysemateriall	Vekt plastfraksjon	% plast i total fraksjon	% plast av TS
	Labeling	Time	Operation parameter							
in flow	7/9 - IA	14:30:00	1A	33%	1A Raw Sludge	4,80%	233	0,012	0,005 %	0,11%
out flow DF	7/9 - B	14:30:00	1A	33%		29,50%				
out flow LF	7/9 - C	14:30:00	1A	33%	1A Filtrate	3,27%	263,8	0	0%	0,00%
in flow	7/9 - D	16:45:00	1D	26%	1D Raw Sludge	4,50%	196,8	0,0102	0,005 %	0,12%
out flow DF	7/9 - E	16:45:00	1D	26%		28,20%				
out flow LF	7/9 - F	16:45:00	1D	26%	1D Filtrate	3,36%	253,1	0	0%	0,00%
in flow	7/9 - G	18:10:00	1H	12%	1H Raw Sludge	4,80%	352,8	0,0271	0,008 %	0,16%
out flow DF	7/9 - H	18:10:00	1H	12%	1H Cake	25,20%	172,3	0,0695	0,04%	0,16%
out flow LF	7/9 - I	18:10:00	1H	12%	1H Filtrate	3,64%	258,4	0	0%	0,00%
in flow	7/9 - J	11:00:00	2D	12%	2D Raw Sludge	4,80%	355,9	0,0125	0,004 %	0,07%
out flow DF	7/9 - K	11:00:00	2D	12%		29,80%				
out flow LF	7/9 - L	11:00:00	2D	12%	2D Filtrate	3,43%	354,6	0	0%	0,00%
in flow	7/9 - J	12:00:00	2F	8,3 %	2F Raw Sludge	4,60%	337,6	0,0015	0,0004 %	0,01%
out flow DF	7/9 - K	12:00:00	2F	8,3 %		31,50%				
out flow LF	7/9 - L	12:00:00	2F	8,3 %	2F Filtrate	3,32%	419,6	0	0%	0,00%
in flow	7/9 - M	13:50:00	2H	0%	2H Raw Sludge	4,50%	367,3	0,0036	0,001 %	0,02%
out flow DF	7/9 - N	13:50:00	2H	0%		28,30%				
out flow LF	7/9 - O	13:50:00	2H	0%	2H Filtrate	3,56%	365,6	0	0%	0,00%
in flow	7/9 - M	14:40:00	2J	0%	2J Raw Sludge	4,60%	368,9	0,001	0,0003 %	0,01%
out flow DF	7/9 - N	14:40:00	2J	0%	2J Cake	30,50%	167,2	0,1461	0,09%	0,29%
out flow LF	7/9 - O	14:40:00	2J	0%	2J Filtrate	4,05%	308,8	0	0%	0,00%

Table 2.3: FRP analysis results for *all* tests, performed in DMFs labs (Fagerheim, 2019).

Table 2.3 shows the results of all tests and suggests that the mean average level of plastic residue in “Raw Sludge” is as low as 0,07% of DM. Given that plastics comprise 96% of foreign objects in bio-fertilizer the total level of foreign objects for these results is lower than the legally-defined threshold as defined by the Norwegian fertilizer regulations. The analysis of “Filtrate” revealed negligible plastic residue fractions, indicating that the FRP have a capacity to reduce plastic residue in bio-fertilizer *significantly*.

Figure 2.3: Plastic residue in sample “Raw Sludge 1H” (Fagerheim, 2019). Figure 2.4: Corresponding plastic residue in sample “Filtrate 1H” (Fagerheim, 2019). *Foto: André Beck Fagerheim*

Figure 2.5: Plastic residue in sample “Raw Sludge 2F” (Fagerheim, 2019). Figure 2.6: Corresponding plastic residue in sample “Filtrate 2F” (Fagerheim, 2019). *Foto: André Beck Fagerheim*

Figure 2.3 and Figure 2.4 show the most extreme reduction of plastic residue while the latter two figures, Figure 2.5 and Figure 2.6, are showing the least extreme reduction of plastic residue in samples from “Raw Sludge” and their corresponding “Filtrate”. Figure 2.4 showing the smallest amount of plastic residue in “Filtrate” while Figure 2.6 showing the biggest amount of plastic residue in “Filtrate” for this analysis.

These results apply to the objectives of our study, as this form of post-treatment technology can reduce plastic residue in bio-fertilizer *significantly.* The average loss of organic material is 23,8% for all tests and an average specific loss of 17% for tests with operational parameters desired by DMF. For the sample showing the highest amount of plastic residue in outflow, the level of plastic residue in “Filtrate 2F” is below 0,01% of DM. Thus, from a conservative estimate, the FRP reduced the level of plastic residue by a minimum of 85,7%, from 0,07% of DM to at least 0,01% of DM.

2.3 Alternative waste bags

The content of this subchapter will firstly include a presentation of the two types of plastic waste bags currently utilized in the collection of OHW to “Greve Biogass”. The presentation will contain its behavior and compatibility with the conditions in and outside the bioreactor. Further, a presentation about the definition of biodegradability will follow, followed by a presentation about three alternatives to PE waste bags. Lastly, the weight reduction potential of OHW in different waste bags will follow, because the storage and handling of OHW can notably affect the weight of organic waste before transportation.

2.3.1 Currently utilized plastic waste bags

The current use of plastic waste bags, be it either from degradable or non-degradable materials, contributes to plastic residue in bio-fertilizer, and thus, the accumulation of plastics in terrestrial ecosystems.

Polyethylene (PE), which is the most common type of plastic, is widely used for the production of plastic waste bags, can be made from either renewable or non-renewable materials. Nonetheless, due to the long carbon chain molecular structure and its hydrophobicity, PE undergoes no degradation in the bioreactor and is otherwise resistant to biodegradation under normal conditions. When exposed to UV radiation and/or mechanical wearing and tearing, PE bags fragments to increasingly small pieces. “Fragmentation degradation” and its resistance to biodegradation contributes to accumulated levels of plastic residue as the time frame for the complete mineralization in soil is unknown.

Compostable bio bags made of renewable materials undergo minor degradation in bioreactors because the conditions for degradation are suboptimal. Compostable bio bags need to be in an environment that fulfills the requirement for industrial composting to be 100% degraded within 30 days. Temperatures above 55°C, more optimally around 70°C, and in an aerobic environment contributes to the fastest degradation of compostable plastics (Rennesvik, 2019). Compared to the bioreactor with temperatures of around 42°C and in an anaerobic environment, the compostable bio bags will undergo minor degradation.

When bio-fertilizer is applied to soil, one would assume that plastic residue from compostable bio bags would degrade relatively fast and would not contribute to the accumulation of plastics in terrestrial ecosystems. However, research regarding compostable plastic degradation in soil is very limited. Currently, Claire Coutris at the Norwegian Institute of Bioeconomy Research-NIBIO, is performing research to determine the behavior of compostable bio bags in soils (Joner, 2019).

2.3.2 European standard for biodegradability – EN 13432

In the bioplastics and paper sector, the European standard EN 13432 is the most important technical reference for manufacturers of materials, public authorities, composters, certifying bodies, and consumers. EN 13432 defines the characteristics and behavior a material must have to be claimed as compostable. The main objective of EN 13432 defines the four characteristics that a material must possess to be considered compostable, namely that it can be materially recycled through either composting or anaerobic digestion.

The following four characteristics which are presented below are presented directly from Novamont Environmental Affairs by Degli Innocenti (2004) and are given as a reference point for which characteristics a compostable material must show to be in accordance with EN 13432.

Biodegradability is, the capability of the materials to be converted into carbon dioxide (CO_2) through the action of microorganisms. This property is measured with a laboratory standard test method: EN 14046 (also published as ISO 14855: biodegradability under controlled composting conditions). To show complete biodegradeability, a biodegradation level of at least 90% must be reached in less than 6 months (*Note: measurement errors and biomass production are experimental factors which can make it difficult to reach 100%, this is why threshold is set at 90%, rather than 100%).*

Disintegrability, namely fragmentation and invisibility in the final compost (absence of visual contamination), measured in a pilot-scale composting test (EN 14045). Specimens of the test material are composted with biowaste for 3 months. The final compost is then screened with a 2 mm sieve. The mass of test material residues with dimensions > 2 mm shall be less than 10% of the original mass (*Note: in this case, a 10% tolerance is allowed, taking into account the typical error found in biological analysis*).

Absence of negative effects on the composting process. Verified with the pilot-scale composting test (EN 14045).

Nearly complete absence of heavy metals (below the given max. values) and the absence of negative effects on compost quality (i.e., reduction of the agronomic value and presence of ecotoxicological effects on plant growth). A plant growth test (modified OECD 208) and other physical-chemical analysis are applied on compost where degradation of test material has happened.

An important note regarding degradable plastics: There is an important difference between biodegradable plastics and oxo-degradable plastics. The former plastic disintegrates and is compostable in accordance with EN 13432, (i.e., over time, it will be completely degraded by microorganisms). The latter plastic disintegrates into microscopic pieces as a fragmentation agent is added to the plastic. However, the microscopic pieces do not further compost, and hence, oxo-degradable plastics present a huge issue regarding the formation and accumulation of microplastics in ecosystems (Rennesvik, 2019).

2.3.3 Commercially available alternative waste bags

Below follows a presentation of commercially available alternative waste bags suitable and compatible for OHW collection and processing through bioreactors.

Biodolomer F30 – Gaia Biomaterials AB

The following text contains work conducted by Fagerheim (2019) preceding this study. Through the EU-funded project called "Life", 3 million euros have been invested to replace materials of fossil origin with materials of renewable origin. These materials should be biodegradable in accordance with EN 13432, and convertible to biogas and bio-fertilizer in biogas facilities. In this context, Gaia Biomaterials AB developed a biodegradable bio film called Biodolomer F30, suitable for conversion and degradation in bioreactors in biogas facilities. Biodolomer F30 is a compound of a biodegradable aliphatic-aromatic copolyester (PBAT), polylactic acid (PLA), and calcium carbonate. The two polymers, PBAT and PLA, which belongs to the polyester family, are derived from potato peelings and rapeseed oil while the calcium carbonate is derived in near proximity to Bergen, Norway as "Dolomittkalk". Calcium carbonate in the form of "Dolomittkalk" has a higher mean magnesium content, which ensures there is a correct pH-value of 7,8 in the bioreactors.

The bio bags made by Biodolomer F30 have been thoroughly tested in several facilities and are compatible with optical sorting facilities. The most important tests have proved that Biodolomer F30 is biodegradable in facilities with Cellwood pre-treatment, as the plastic residue entering the bioreactor is small enough to be degraded within 30 days. Hence, no visible plastic residue is presented in bio-fertilizer according to Gaia Biomaterials (2018) and Rosén (2019).

Paper bags – Total Packaging AS

During an enterprise visit at Total Packaging and Total Holding AS in Fredrikstad, Norway the following information was gathered by interviewing Jensen (2019).

During the 1990s it was common to utilize paper waste bags in municipal waste handling. However, negative experiences with the paper waste bags like bottom tearing resulted in a relatively quick transition to bio bags because bottom tearing presented a huge practical issue, and, eventually, bio bags acquired most of the waste bag market.

Recently, the growing awareness regarding climate change, environmental concerns, and plastic pollution, have resulted in a rapid increase in paper waste bag demand. With the invention of new paper and paper bag technology, in addition to kitchen waste handling systems adapted to paper bags, paper waste bags are very likely to re-emerge as a sustainable and desirable waste bag.

Currently, Total Packaging AS and Total Holding AS deliver both paper waste bags and paper waste bag systems to private and commercial customers. The wet strength paper, named EcoComp, utilized in the paper waste bags is produced by Mondi Dynäs AB located in

Sundsvall, Sweden. Long and slow-growing fibers from virgin material are utilized in the production of EcoComp and provide the product with unique qualities suitable for waste handling. The conversion of the wet strength paper to paper bags is performed by Svenco Pappersäcker located in Arlandastad, Sweden. Both the paper and glue utilized to produce paper waste bags are certified as 100% biodegradable material by EN13432. The measurements of the paper waste bags delivered for the collection of OHW is 28x13x40 mm and 22x17x36 mm.

When paper waste bags become moist, the mechanical properties decrease, which increases the possibilities of bottom tearing. However, when paper waste bags are applied to open bin solutions, meaning total aeration of the bag, including no lit, bottom tearing is hardly observed.

For further usage in modern solid waste management systems, closed paper waste bags have been tested in underground sucking solutions with positive results. Biodegradation in bioreactors is 2-3 weeks, and the remaining fibers from the paper waste bags act as a fiber and carbon source in bio-fertilizer, which farmers favor.

Bio bags – BioBag World

During an enterprise visit at BioBag World in Askim, Norway the following information was gathered by interviewing Rennesvik (2019).

Biodegradable bio bags delivered by BioBag World, Mater-Bi, are composed of renewable materials and compostable polyester from fossil origin. The renewable materials originate from corn and potato starch, as well as vegetable oils like rapeseed, sunflower, and thistle oil used for the manufacturing of compostable polyester. It is emphasized by BioBag World that Mater-Bi does not contain any traditional plastic of fossil origin.

The crystallization of polymers is a process associated with the partial alignment of their molecular chains. Non-degradable plastics which are exposed to UV radiation fragments to increasingly smaller pieces through photodegradation. Biodegradable plastics, like the compostable polyester utilized in Mater-Bi, have a structural gap in their crystalline structure which makes the whole structural chain available to living organisms, bacteria, fungi, and algae. Hence, the compostable polyester will be fully degraded.

Compostable plastics degrade fastest during industrial composting with temperatures around 70°C and in an aerobic environment. Aerobic conditions are traditionally maintained through regular turning the compost windrows. Additional porosity of the windrows is obtained through the injection of tiles and wood chips.

Biodegradation of Mater-Bi starts as soon as contact is established with organic waste, however, the rate of biodegradation variates significantly with the conditions. During its journey through the bioreactor, in a «wet process», the conditions for degradation increases, however, the time spent, 30 days, only results in minor degradation of the Mater-Bi. For complete degradation of Mater-Bi industrial composting is recommended as an addition.

During the 1990s when the bio bags first entered the market an unfavorable bottom welding resulted in fractured bio bags. Closed and unaerated waste handling systems also resulted in excess moisture and positive conditions for biodegradation resulting in severely reduced mechanical properties and bottom tearing as a result. Newer and adapted bottom welding of the bio bags in combination with fully aerated waste handling systems makes bottom tearing something of the past.

Comparison of Paper Bags and Bio Bags

The enterprise visits at both Total and BioBag World proved both pros and cons with their respective products and waste bags solutions. Both paper and bio bags equally serve as a well-functioning waste bag given that they are both utilized in waste handling systems which enables aeration and ventilation during storage. The most notable downside to bio bags is the deterioration of quality under long-term storage, and especially storage under unfavorable conditions, such as moisture and temperature fluctuations. However, frequent procurement of bio bags decreases the need for storage. The most notable downside with paper bags is the share volume paper bags occupy. As general rule, the storage of the same amounts of paper bags require five times more volume as bio bags.

2.3.4 Weight reduction potential in PE, bio and paper bags

The weight reduction potential obtained through evapotranspiration can notably reduce the level of water in OHW if stored and handled optimally before transportation – potentially saving costs and emissions. Hence a presentation of three different studies will follow, as several factors contributes to the future choice of waste bags by waste collectors and biogas and bio-fertilizer producers.

Avfall Sverige – paper, bio, and PE bags

Avfall Sverige conducted a study that involved comparing three different types of waste bags and their weight reduction potential (Avfall Sverige, 2010). The following types of waste bags where compared: Optical waste bags (PE waste bags), bio bags (Mater-Bi) and paper bags.
All waste bags were kept in kitchen conditions for 3 days, with an average temperature of 20°C and 50% relative humidity, followed by either 14 or 7-day storage in ventilated or unventilated waste containers with an average temperature of 18°C and 70% relative humidity, as illustrated in Figure 2.7.

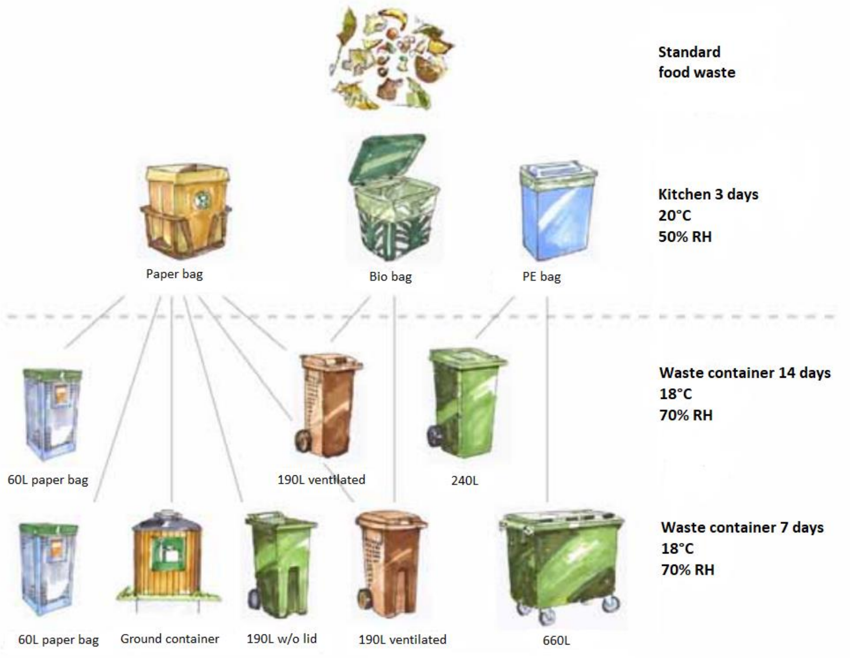


Figure 2.7: The different storage practices of OHW (Avfall Sverige, 2010).

In the system that utilizes paper bags, a 12% weight loss was observed during the kitchen condition phase while the total weight loss for the paper bag system showed an 18-32% total weight reduction with an average value of 27%.

In the system which utilized bio bags, a 7% weight loss was observed in kitchen conditions while the total weight loss for the bio bag system observed where 10%.

Optical plastic bags showed a weight reduction potential of 2-4% with an average of 2%.

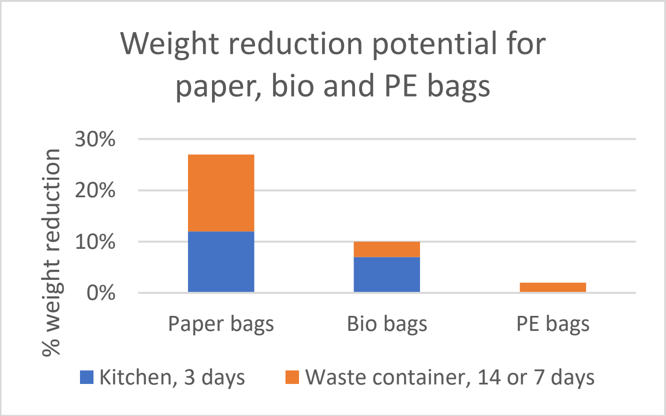


Figure 2.8: Accumulated wet weight reduction (w%) in OHW collected in paper, bio, and PE bags in different waste collection systems (Avfall Sverige, 2010).

This weight reduction potential shown in Figure 2.8 between different types of waste bags, although heavily affected by storage methods is clearly visible in this study. PE bags are stored in unventilated bins w/lid, bio bags are stored in ventilated bins w/lid, and paper bags are stored in ventilated bins w/o lid. The storage and handling after the kitchen in waste containers also varies for the different types of waste bags. Hence, which type of waste bag has the biggest weight reduction potential is not conclusive because all waste bags are stored and handled in different waste collection systems.

Jordforsk – Bio bags in ventilated and closed pails

Jordforsk conducted experiments with bio bags (Mater-Bi) used to collect OHW (Aasen, 2004). The study focused on weight reduction, mold, and odor development in the bio bags. A wide variety of fresh organic foods were chopped and placed in the bio bags. The bio bags were stored for 8 days, 60-80 cm above the floor, in a ventilated and heated room with a constant temperature of 20°C and an average relative humidity level of 35%. The different samples were measured daily, regarding weight reduction, mold, and odor development. The bio bags were placed in three different pails while a fourth one was closed with a simple knot to measure the degree of evaporation through the polymer film.

Figure 2.9 illustrates the three different pails utilized in the study:
(a) Ventilated 5 L AirMax pail w/lid, (b) Ventilated 5L AirMax pail w/o lid, and (c) Unventilated 10L pail w/lid.

Figure 2.9: The three different pails used for the experiment, (a) to (c) from left to right (Aasen, 2004).

Figure 2.10 shows the weight reduction which was observed in the different pails systems.

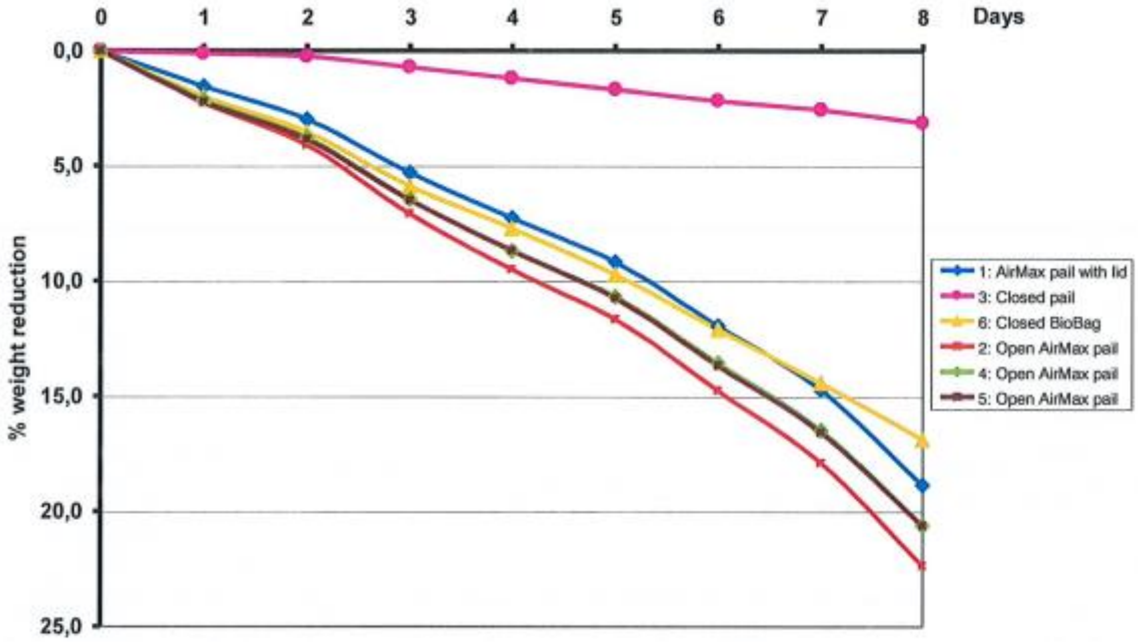


Figure 2.10: Accumulated wet weight reduction (w%) in OHW stored in bio bags in different pails (Aasen, 2004).

The open ventilated pails had the highest weight reduction, 20-22%, where pail 2 (22% weight reduction) had an additional ventilation grid installed at the bottom, which may explain the slightly higher weight reduction compared to the two other open pails. The ventilated pail w/lid had a weight reduction of around 19%, whereas the closed bio bags had a weight reduction of around 17%. The closed pail had a weight reduction of around 3% after eight days. In addition to the measurement of weight reduction, mold, and odor development, the conditions of the bags were observed. All bio bags could be lifted out of the pails after eight days without rupture and no unpleasant smells could be noticed from the bio bags when sealed in the top.

This study suggests important storage and handling options for users of bio bags, as well as waste collectors. In a fully ventilated OHW collection system, the weight reduction is proven to be as high as 22% while the evaporation through the closed bio bags shows a weight reduction of 17%. This is of interest as it shows a notable weight reduction potential for the bio bags when stored under optimal conditions, as well as the breathability of the Mater-Bi material in closed bags.

Novamont – BioBags and PE bags in ventilated and closed pails

A similar experiment was conducted by Novamont, where three similar waste pail systems where tested (Razza, 2017). The weight reduction potential and odor development were the focus of the study. The three different waste pail systems tested were the following: (a) Ventilated pail w/lid, (b) Ventilated pail w/o lid, and (c) Closed pail. For each system, bio bags (Mater-Bi) and traditional PE bags were applied and the weight reduction was measured on the 3rd, 4th, and 7th days. Temperature and relative humidity were measured, but not stated in the report.

Table 2.4 displays the weight reduction observed in Novamont's experiment conducted by Razza (2017).

	Weight reduction average values (%)		
System	**3rd day**	**4th day**	**7th day**
Closed pail, BioBag	0,82	1,15	1,89
Closed pail, PE bag	0,81	1,05	1,66
Ventilated pail w/o lid, BioBag	13,15	17,38	27,66
Ventilated pail w/o lid, PE bag	8,8	11,35	18
Ventilated pail with lid, BioBag	6,61	9,31	17,73
Ventilated pail with lid, PE bag	1,29	1,8	4,79

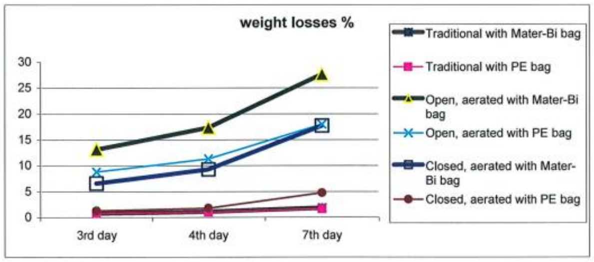


Table 2.4: Accumulated wet weight reduction (w%) in OHW stored in bio bags and PE bags in ventilated and closed pails (Razza, 2017).

We see a similar weight reduction of less than 2% for both bio bags and PE in closed pails, suggesting this way of storage is particularly undesirable for weight reduction. The surprising numbers from this study suggest a weight reduction of 18% for ventilated pail w/o lid for PE bags. The results from this study are even more important to consider as bio bags and PE bags have been equally stored and handled, showing a notable weight reduction of PE bags when stored and handled in optimal waste collection systems.

3 Methodology

In this chapter, the methodology used in this study is described. This chapter is further devided into four subchapters. The first subchapter contains the overall research approach and how the work and data collection for this thesis has been performed. The second subchapter will present the case study for DMF (i.e., detailing the facility and suppliers of organic waste). Thirdly, the process model for DMF is presented, and lastly, the Material Flow Analysis (MFA), scenarios, assumptions, sensitivity and uncertainty are presented.

3.1 Overall research approach

For this thesis, the overall research and data collection approach included literature study, enterprise visits, interviews, and the reviewing of reports. All approaches served to form a foundation for our calculations and analyses, models, and assessments toward mapping the various upstream mass flows and reducing plastic residue in bio-fertilizer.

The literature study has covered the different aspects necessary for this study in accordance with the objectives. Several studies and reports have been reviewed and are presented in chapter 2 Literature. The studies and reports reviewed contain information about plastic residue in substrate and bio-fertilizer, the behavior of different waste bags in different environments and post-treatment technology and its impact on plastic residue level in bio-fertilizer.
Parallel to performing a literature study, several enterprise visits and interviews have been conducted to gather information about alternative waste bags and are presented in Chapter 2.3.3.

Secondly, an upstream analysis has been conducted, which includes the level of organic waste, level of foreign objects, and waste collection methods for the individual suppliers of organic waste to DMF. The data necessary for conducting the upstream analysis has been gathered through interviews with all suppliers of organic waste to DMF, including some suppliers and distributors of plastic waste bags. The level of foreign objects and composition of organic waste delivered to DMF have been gathered through reviewing and comparing individual pick-analyses for the individual suppliers. The pick-analyses reviewed have all been carried out in accordance with the guidelines stated in “Veileder-plukkanalyser” given by “Avfall Norge”. A summary of the guidelines in “Veileder-plukkanalyser” and reference is presented in appendix A.3.

Based on the data collected through the different approaches, a process model and MFA was developed. The MFA was utilized to quantify the different mass flows in DMF, namely the wet weight layer, dry matter layer, and plastic weight layer in the model. From the input data and parameters received, one can assume the level of plastic residue in bio-fertilizer corresponds with the amounts of plastics entering DMF. Hence, the model has been utilized to develop several future scenarios based on different measures to reduce upstream sources of plastic. All future scenarios are compared to the base scenario of 2018.

A sensitivity analysis has been carried out to estimate the biggest uncertainties in our system and how they affect the results. The model and its results have further been used to discuss measures and recommendations to further improve the current situation at DMF and other actors in the solid waste management sector.

3.2 Den Magiske Fabrikken case description

"Greve Biogass" produces biogas and bio-fertilizer from wet organic waste, liquid animal manure (LAM) and liquid organic industrial waste (LOIW). Local collective transport and waste handling services utilize the biogas while 42 local grass and grain farmers utilize the bio-fertilizer. Local greenhouses have also implemented the bio-fertilizer in successful trials and are positive to opt for bio-fertilizer instead of synthetic fertilizers to contribute to a circular economy according to Madsen (2018).

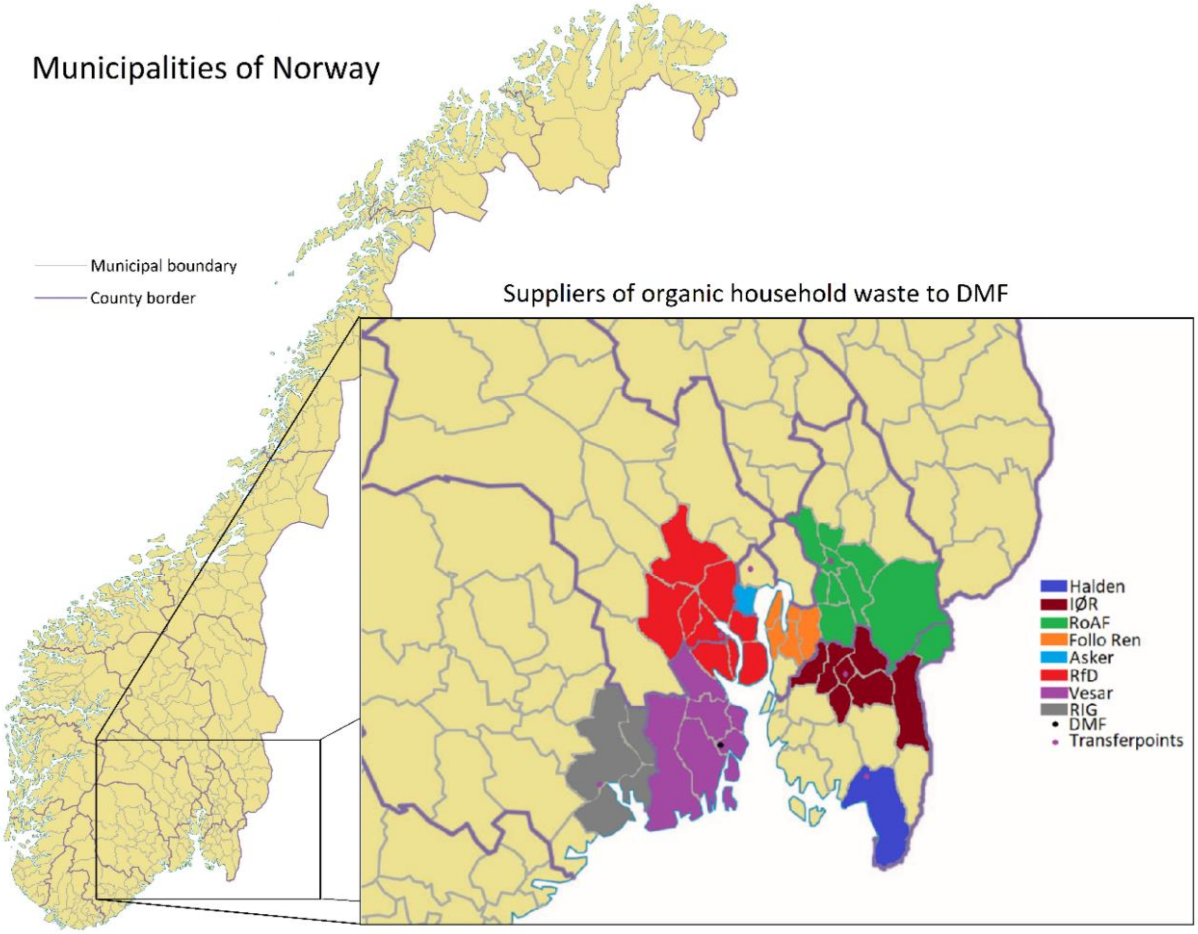


Figure 3.1: Municipalities of Norway and suppliers of OHW to DMF. Self-work adapted from *Kartverket* (n.d.).

The wet organic waste consists of both OHW and COW. OHW originates from as many as 1 million households in the Oslo-fjord area while COW originates from a host of local and regional industrial food cooperatives and corporations. The main collectors of OHW, as depicted in Figure 3.1, are Renovasjon i Grenland (RiG), Vesar, Renovasjonsselskapet for Drammensregionen (RfD), Asker kommune, Indre Østfolf Renovasjon (IØR) and Romerike avfallsforedling (RoAF) - including the sub-collectors Follo Ren and Halden kommune. Lindum, a regional solid waste management company has the main responsibility of transporting OHW from collectors to DMF.

OHW is collected and transported in plastic waste bags. The plastic waste bags utilized in the collection of OHW are in most cases made from virgin polyethylene (PE). In some cases, plastic waste bags are made from compostable materials or recycled PE. Along with the utilization of plastic waste bags, the OHW includes incorrectly sorted waste in the form of plastic packaging and other foreign objects (FOs).

COW is delivered directly from suppliers, most often entirely in its original packaging.

Both OHW and COW, independent of source and composition, are feed from the receiving bunker to pre-treatment without any pre-sorting. This step is crucial to understand, because there exists no separation of organic waste from the plastics before the inhomogeneous mass is fed to pre-treatment, mixing organic waste and plastics into a substrate.

Before pre-treatment, all materials go through a grinder, where both organic waste and plastics are torn and fragmented to small pieces. Plastics, along with especially hard and in-moldable organic material, are rejected in the separator delivered by Cellwood. Hard objects such as eggshell, stone, and sand are rejected through a hydrocyclone. Remaining organic material and plastics enter further pre-treatment before entering the bioreactor as a substrate. See chapter 2.2.2 for more details surrounding pre-treatment in DMF. Plastic residue in the substrate from compostable bio bags undergoes minor degradation in the bioreactor while non-degradable plastic residue persists through the whole process, ending up in bio-fertilizer.

Uniquely compared to other biogas facilities in Norway, DMF utilizes LAM as dilution water during pre-treatment. The addition of LAM counteracts the reduction and dilution of dry matter in the substrate, hence increasing biogas output from bioreactor (Hegg, 2019).

Pre-treatment technology delivered by Cellwood is utilized and the separator is responsible for reducing the level of plastics and other FOs from entering the bioreactor. On the contrary, because mostly soft and moldable organic material will pass through the separator, hard organic material will be rejected. Depending on the organic material being received at DMF, rejected organic material will vary accordingly. On average, 20% of organic waste is rejected in pre-treatment and sent for incineration (Hegg, 2019).

Previously mentioned, farmers are imposing stricter demands on biogas companies, “Greve Biogass” among them. Unless visible amounts of plastics are reduced in bio-fertilizer, farmers will refuse to accept bio-fertilizer delivered by biogas companies. “Greve Biogass” is intented to satisfy both farmers and consumers, as the company itself has the goals and ambitions to find the methods that result in the least possible loss of organic material and the biggest possible rejection of FOs, including plastics. Preheating of the substrate before entering the separation is one way of making hard and in-moldable organic material more moldable, and there are many possible post-treatment solutions available to reduce plastics residue in bio-fertilizer. The former and latter initiatives are both are under planning and testing in the facility of “Greve Biogass”.

3.2.1 Suppliers of OHW to DMF

The following subchapter will include a presentation of the suppliers of OHW and their respective waste collection practices. It also includes a transparent overview of the data collection for our modeling and calculations. Firstly, this subchapter will present the three suppliers, RoAF, Follo Ren, and Halden, because they share the same practice of collection, followed by an individual presentation of the remaining suppliers. Lastly, a note regarding COW will be presented as well. A summary of the data collected, practices, additional details, and references will be presented in Subchapter 3.2.2. Further, a detailed presentation of the population within the supplier’s area of responsibility is presented in appendix A.1.

RoAF, Follo Ren, and Halden

“Romerike Avfallsforedling” (RoAF), is an intermunicipal solid waste management company located in Romerike, north-east of Oslo. RoAF has the following municipalities under their area of responsibility, Sørum, Fet, Rælingen, Enebakk, Lørenskog, Skredsmo, Nittedal, Gjerdrum, Aurskog-Høland, and Skedsmo. In addition, to handle the municipal solid waste under their area of responsibility, RoAF receives municipal solid waste from Follo Ren and Halden Municipality. The combined population of RoAF, Follo Ren, and Halden Municipality is estimated to be 348153, whereas the municipalities of RoAF constitutes 203135 inhabitants, with around 90000 households.

Follo Ren has five municipalities under their area of responsibility, Nesodden, Frogn, Ås, Oppegård, and Ski. The population in the municipalities of Follo Ren is estimated to be 113841 distributed on 43000 households. Compared to other suppliers of OHW which started sorting their OHW in January 2014, Follo Ren started sorting their OHW 1st of October 2017, complementing the new practice with a pick-analysis 6 months later.

Halden Municipality is in the southernmost part of Østfold county. With a population of 31177 distributed roughly on 12990 households, Halden Municipality is the smallest supplier of OHW.

In January of 2014, RoAF established an advanced optical sorting facility (ESAR) in the vicinity of Skredsmo. The optical sorting facility separates the municipal solid waste into five main categories, OHW, plastics, paper, metals, and residual waste to incineration. The plastics are further separated into five categories, namely PET, PP, LDPE, HDPE, and mixed plastics. RoAF, Follo Ren, and Halden Municipaliy all share the same method of waste collection, as all municipal solid waste goes through the ESAR facility. Green PE waste bags are utilized for the collection of OHW while municipal solid waste and plastic waste are collected in non-green PE waste bags. Both the green PE waste bags and the non-green PE waste bags are distributed in mixed trash bins outside each respective household. In a few cases, the green PE bags are distributed in separate trash bins, such as in Halden Municipality, where both separated and mixed containers exist.

The green PE waste bags utilized for the collection of OHW by Halden and Follo Ren undergoes *more* handling compared to the OHW collected in the municipalities of RoAF. OHW is collected in trash bins and transported in waste trucks to the municipal solid waste transfer points. The OHW is then offloaded on concrete surfaces, reloaded to containers by loaders, transported to the ESAR facility, and again offloaded to concrete surfaces before being handled by loaders. It should be mentioned that the green PE waste bags are not mechanically compressed during any of the transport stages, however, natural compression affects the green PE waste bags at the bottom of the waste trucks. Having endured a considerable amount of handling, the green PE waste bags endure additional handling throughout the ESAR facility, where the bags experience drops before being transported in containers to DMF.

The green PE waste bags utilized by RoAF, Follo Ren, and Halden Municipality have thorough specifications than other suppliers of OHW as the handling both before, but especially throughout the ESAR facility demands higher mechanical strength and toughness. Among suppliers of OHW, it has been established that plastic waste bag thickness is associated with strength and quality. However, producers of plastic waste bags state the opposite; the thickness does not equal quality and plastic waste bags of high strength and quality can be made more efficient, as stated by Rishaug (2019) at Rullpack AB.
This is illustrated in the different thicknesses and weights between the plastic waste bags utilized by RoAF and Follo Ren and those used in Halden Municipality. Specifications given by RoAF to distributors of plastic waste bags require the average thickness of the plastic waste bags to be 28 µm while Halden Municipality requires the minimum thickness to be 25 µm. The plastic making up the plastic waste bags utilized by suppliers of OHW to optical sorting facilities is low-density polyethylene (LDPE). Comparing LDPE and high-density polyethylene (HDPE), the ductile strength is high in LDPE while it is low in HDPE, making LDPE most suitable in conditions in which the risk for tearing and fracture is high.

Analysis conducted by RoAF in 2018 estimated a 29% loss of OHW throughout the ESAR facility, however, measures were introduced and analysis conducted in 2019 estimated a 19% loss of OHW. The losses are mainly taking place due to partial or total fracture of the green PE waste bags. The improved loss rate from 2018 to 2019 was mainly achieved by replacing sharp edges with blunt edges in the vibration strainer and by improving the wheel loader by introducing a wider shovel and replacing the sharp bottom scraper of steel with one of plastic (Skovly, 2019).

Since the establishment of the advanced optical sorting facility and the respective sorting of OHW, as of January 2014, several pick-analyses have been conducted within RoAF's area of responsibility. One of the main goals behind the pick-analyses was to measure and estimate the composition of organic waste and the percentage of organic waste being sorted as OHW. The pick-analyses have been conducted in mainly two determined areas from 2014 to 2019. Four extraction points in the municipality of Aurskog-Høland have contributed to the pick-analyses conducted in 2015 and 2017 while eight extraction points in the remaining eight municipalities have contributed to the pick-analysis conducted in 2016, 2018, and 2019. In 2019, in addition to the established extraction points, one extraction point in the municipality of Næring was also included. We have chosen the pick-analyses conducted in 2016, 2018, and 2019 as they provide a more representable data from RoAF's households because they include data from far larger areas than those of the pick-analyses conducted in 2015 and 2017.

In 2019, 2,3 tons of municipal solid waste was sorted to detail in March. In 2018, 2,4 tons of municipal solid waste was sorted to detail in March. In 2016, 2,2 tons of municipal solid waste was sorted to detail in November. The levels of incorrectly sorted plastics are estimated from weighted average of the latter mentioned pick-analyses because they include a sufficient analysis of the composition of the green PE waste bags.

For Follo Ren, pick-analysis was carried out in spring 2018, 6 months after commenced OHW sorting to determine the level of sorting for their newly established practice. A specific pick-analysis was also carried out for the green PE waste bags. However, this pick-analysis provided an insufficient composition of the green PE waste bag because the level of incorrectly sorted plastics was left out. The following pick-analysis conducted in the spring of 2019 assumed the composition of the green PE waste bags equal to that of spring 2018. Hence our data from Follo Ren is based on the pick-analyses from 2018. The level of incorrectly sorted plastics is estimated from weighted average of all pick-analyses reviewed for this paper.

Halden Municipality provided us with their pick-analysis from 2018 which included an insufficient analysis of the green PE waste bag–excluding the level of incorrectly sorted plastics. The level of incorrectly sorted plastics is estimated from the weighted average of all pick-analyses reviewed for this paper.

IØR

IØR, is an intermunicipal solid waste management company covering north and north-east of Østfold province. Askim, Eidsberg, Spydeberg, Hobøl, Marker, Skiptvet, and Trøgstad are the municipals under IØR's area of responsibility, constituting 51709 inhabitants and 25600 households. IØR utilizes green PE waste bags, which is made up of 50% recycled plastic and have separate trash bins for its OHW. The OHW is transported in garbage trucks to a transfer point before being loaded in containers and transported to DMF. Unfortunately, no pick-analyses could be provided for our study as no pick-analyses have been conducted in IØR's area of responsibility. Hence the level of incorrectly sorted plastics is estimated from the weighted average of all pick-analyses reviewed for this paper.

Asker

Asker Municipality, located furthest east in Akershus county, has a population of 61523 inhabitants distributed in 22331 households. Asker Municipality handles its OHW through utilizing transparent green PE waste bags, made by 80% renewable materials and have separated trash bins for its OHW. Asker Municipality provided us with their pick-analysis from 2018 which included a sufficient analysis of their green PE waste bag.

RfD

"Renovasjonsselskapet for Drammensregionen" (RfD), is an intermunicipal solid waste management company with the following municipalities under their responsibility: Drammen, Hurum, Lier, Modum, Nedre Eiker, Røyken, Sande, and Svelvik. The municipalities are located in the south-east of the province of Buskerud province and in the north-east of Vestfold province. The municipalities under RfDs area of responsibility have a combined population of 202111 distributed in 88820 households. RfD utilizes brown PE waste bags made of 100% recycled PE for their collection of OHW in separate trash bins. These plastics bags are slightly thicker than virgin PE waste bags, as the mechanical strength is reduced in recycled plastic waste bags. RfD presents annual reports providing the public with the results from their pick-analyses. In our study, we utilized the data gathered in 2017 about the composition of the OHW bags as the data presented from 2018 are assumed the same as in 2017.

Vesar

"Avfallsselskapet i Vestfold"-Vesar, is an intermunicipal solid waste management company with the following municipalities under their responsibility: Horten, Holmestrand, Larvik, Færder, Sandefjord, Tønsberg, and Re. Vesar utilizes bio bags (Mater-Bi) in their collection of OHW which is collected from separate containers. With a population of 234471 distributed in 112000 households, Vesar is the biggest supplier of OHW to DMF. Vesar provided us with their pick-analysis from 2017 which included the composition of the OHW bags including the level of incorrectly sorted plastics.

RiG

”Renovasjon i Grenland” (RiG) is an intermunicipal solid waste management company located in Grenland, east in the province of Telemark. The municipalities under RiGs responsibility are Skien, Porsgrunn, Bamble, and Siljan, with a population of 107287 distributed in 32412 households. RiG utilizes green PE waste bags for the collection of OHW which is collected from mixed containers and sorted in an optical sorting facility. The optical sorting facility is operated by “Bjorstaddalen Husholdning” with the technology delivered from the Swedish company “Envac Optibag”. The loss of OHW has been observed to a minimum throughout the optical sorting facility. Comparing the data provided by Breiland (2019) with parameters provided by Høines (2019), 90% of the green PE waste bags distributed to the households in RiG are utilized for the collection of OHW. The remaining 10% of the bags are utilized for other purposes within the households, as they are not returned to the optical sorting facility.

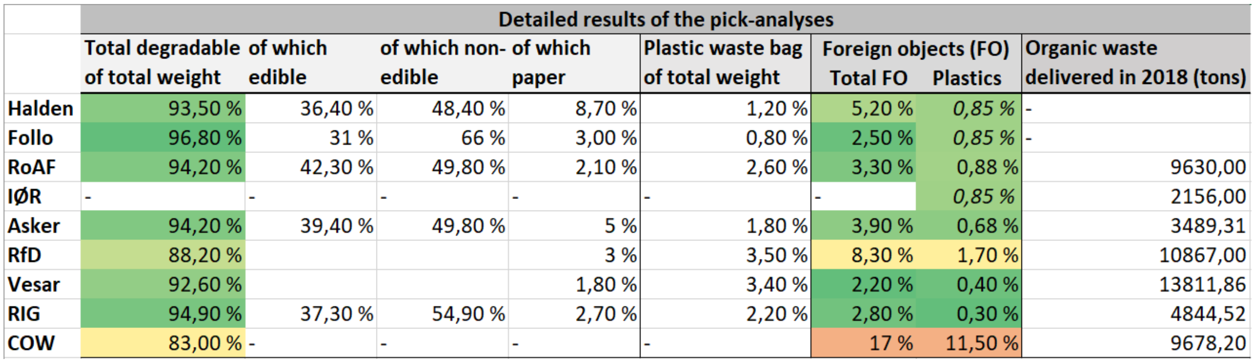
We were provided with two pick-analyses for this paper. One pick-analysis was conducted by “Greve Biogass” in 2015, comparing the OHW delivered by RiG and Vesar. However, this pick-analysis proved to be unfavorable for RiG because the level of incorrectly sorted plastics was far higher than average. This was due to a technical glitch in RiGs optical sorting facility which left several bags of sorted plastics in the container with OHW and was counted as incorrectly sorted plastics in the pick-analysis. For our paper we have chosen the pick-analysis from 2017 as a foundation for our calculations as it provided a complete composition of the green PE waste bags.

Commercial organic waste

A total of 9678,20 tons of COW were delivered to DMF throughout 2018 from various sources. The suppliers of Ragn-Sells AS, Norsk Gjenvinning AS, and Pronova BioPharma Norge AS and their respective subsidiaries are dominating the supply chain of COW. In 2017, these suppliers constituted over 80% of the delivered COW to DMF (Hammer, 2018).

3.2.2 Summary of data from suppliers of OHW and COW

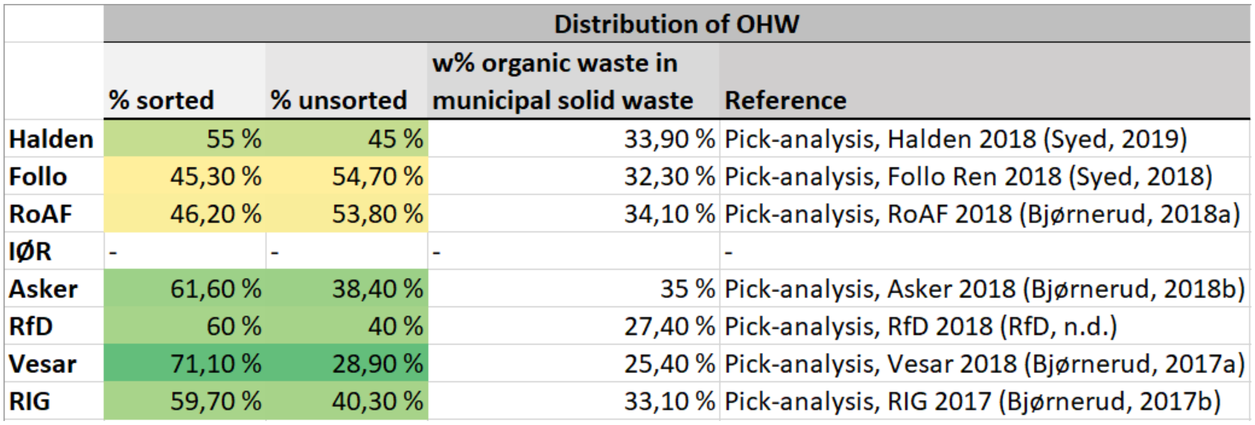
Table 3.1. shows a summary of the data from the different suppliers with all values given in percent of wet weight (WW). The total degradable content is the amount of degradable materials which is further divided into edible, non-edible, and paper. The waste bag column shows how much the plastic waste bag makes up of total weight, and finally, the FOs indicate how much non-intended material is in organic waste, showing the total amount and total percentage of plastics in OHW and COW. For the column "Total degradable", darker green indicates the highest level while light green and yellow indicate the lowest levels of degradable content. For the "Foreign objects (FO)" columns, dark green indicates the lowest levels while yellow and orange indicate the highest levels of foreign objects and plastics. For references, see appendix A.5.



	Detailed results of the pick-analyses							
	Total degradable of total weight	of which edible	of which non-edible	of which paper	Plastic waste bag of total weight	Foreign objects (FO)		Organic waste delivered in 2018 (tons)
						Total FO	Plastics	
Halden	93,50 %	36,40 %	48,40 %	8,70 %	1,20 %	5,20 %	*0,85 %*	-
Follo	96,80 %	31 %	66 %	3,00 %	0,80 %	2,50 %	*0,85 %*	-
RoAF	94,20 %	42,30 %	49,80 %	2,10 %	2,60 %	3,30 %	0,88 %	9630,00
IØR	-	-	-	-	-	-	*0,85 %*	2156,00
Asker	94,20 %	39,40 %	49,80 %	5 %	1,80 %	3,90 %	0,68 %	3489,31
RfD	88,20 %			3 %	3,50 %	8,30 %	1,70 %	10867,00
Vesar	92,60 %			1,80 %	3,40 %	2,20 %	0,40 %	13811,86
RIG	94,90 %	37,30 %	54,90 %	2,70 %	2,20 %	2,80 %	0,30 %	4844,52
COW	83,00 %	-	-	-	-	17 %	11,50 %	9678,20

Table 3.1: Detailed results of the pick-analyses.

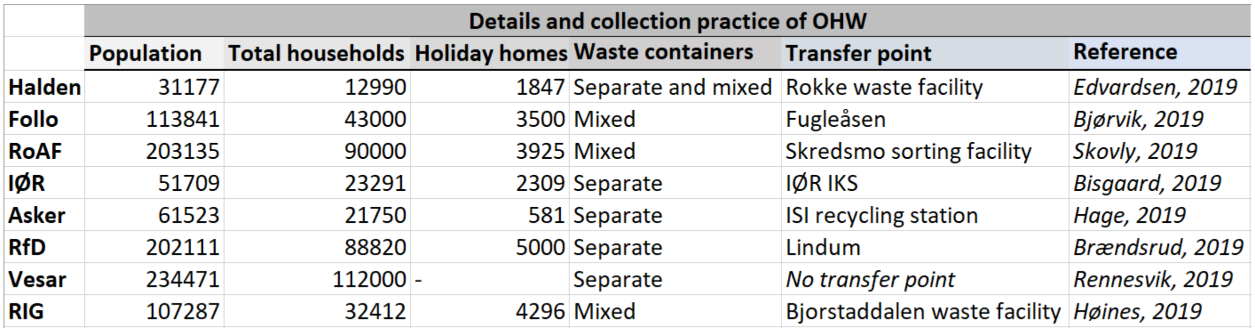
Table 3.2 shows the distribution of sorted and unsorted OHW for each supplier. Sorted OHW is collected and sent for material recycling in DMF while unsorted OHW is disposed of as municipal solid waste and sent for incineration. For "% sorted", darker green showing highest levels while light green and yellow showing lowest levels of sorted OHW. Given the latter description, the opposite applies for "% unsorted".



	Distribution of OHW			
	% sorted	% unsorted	w% organic waste in municipal solid waste	Reference
Halden	55 %	45 %	33,90 %	Pick-analysis, Halden 2018 (Syed, 2019)
Follo	45,30 %	54,70 %	32,30 %	Pick-analysis, Follo Ren 2018 (Syed, 2018)
RoAF	46,20 %	53,80 %	34,10 %	Pick-analysis, RoAF 2018 (Bjørnerud, 2018a)
IØR	-	-	-	-
Asker	61,60 %	38,40 %	35 %	Pick-analysis, Asker 2018 (Bjørnerud, 2018b)
RfD	60 %	40 %	27,40 %	Pick-analysis, RfD 2018 (RfD, n.d.)
Vesar	71,10 %	28,90 %	25,40 %	Pick-analysis, Vesar 2018 (Bjørnerud, 2017a)
RIG	59,70 %	40,30 %	33,10 %	Pick-analysis, RIG 2017 (Bjørnerud, 2017b)

Table 3.2: Distribution of sorted and unsorted OHW.

Table 3.3 shows the details and collection practices for the suppliers of OHW. The population is distributed in the households from where OHW is collected and delivered to DMF. OHW from holiday homes is collected as municipal solid waste by local waste collectors and are not included in our calculations as it is sent for incineration. The transfer points show where OHW is redistributed, either directly to DMF or via an optical sorting facility.



	Details and collection practice of OHW					
	Population	**Total households**	**Holiday homes**	**Waste containers**	**Transfer point**	**Reference**
Halden	31177	12990	1847	Separate and mixed	Rokke waste facility	*Edvardsen, 2019*
Follo	113841	43000	3500	Mixed	Fugleåsen	*Bjørvik, 2019*
RoAF	203135	90000	3925	Mixed	Skredsmo sorting facility	*Skovly, 2019*
IØR	51709	23291	2309	Separate	IØR IKS	*Bisgaard, 2019*
Asker	61523	21750	581	Separate	ISI recycling station	*Hage, 2019*
RfD	202111	88820	5000	Separate	Lindum	*Brændsrud, 2019*
Vesar	234471	112000	-	Separate	*No transfer point*	*Rennesvik, 2019*
RIG	107287	32412	4296	Mixed	Bjorstaddalen waste facility	*Høines, 2019*

Table 3.3: Details and collection practices for suppliers of OHW.

Table 3.4 contains the details surrounding the plastic waste bags utilized by each supplier. The "bags per week" parameter as provided either directly or indirectly from each supplier. In the case of Asker, "bags per week" is estimated from the mean average of all "bags per week". Details regarding plastic waste bag calculations are found in Chapter 3.4.

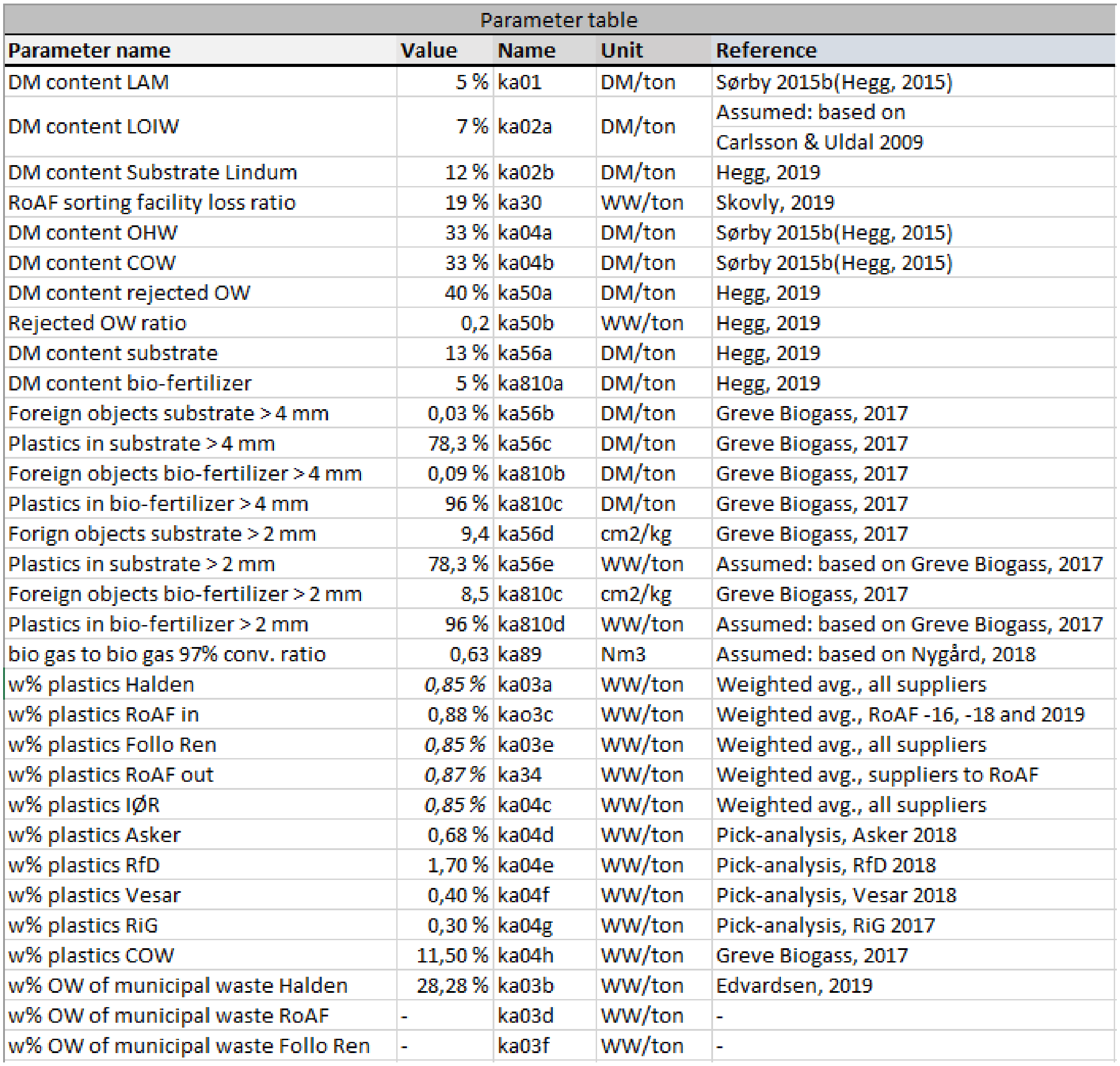
	Plastic waste bag details					
	Type of plastic	**Distributors of plastic waste bags**	**Weight per bag**	**Thickness of bag**	**Bags per week**	**Reference**
Halden	LDPE	Namdal ressurs	8,9g	> 25 µm	1,69	*Edvardsen, 2019*
Follo	LDPE	Tommen Gram	12,2g	30 µm	3	*Bjørvik, 2019*
RoAF	LDPE	Enviropac	12g	28 µm	3	*Skovly, 2019*
IØR	MDPE	Scanlux Packaging	7g	-	2,7	*Bisgaard, 2019*
Asker	HDPE	BioBag World	5,6g	14 µm	2,66	*Hage, 2019*
RfD	HDPE	BioBag World	7,3g	18 µm	2	*Brændsrud, 2019*
Vesar	Mater-Bi	BioBag World	5,65g	14 µm	3,34	*Rennesvik, 2019*
RIG	LDPE	Procurator	7,7g	20 µm	2,9	*Høines, 2019*

Table 3.4: Plastic waste bag details from the suppliers.

3.3 Parameters, flows, and process model

Here follows the presentation of the parameters (Table 3.5) used to calculate the flows (Table 3.6) for the different layers in our process model (Figure 3.2). The process model further served as the foundation for the MFA where the different mass layers and flows within them have been calculated. The results from the different layers (i.e., wet weight layer, dry matter layer and plastic weight layer) will be presented in Chapter 4.2.

Firstly, a presentation of the parameters used for calculating the flows is presented.

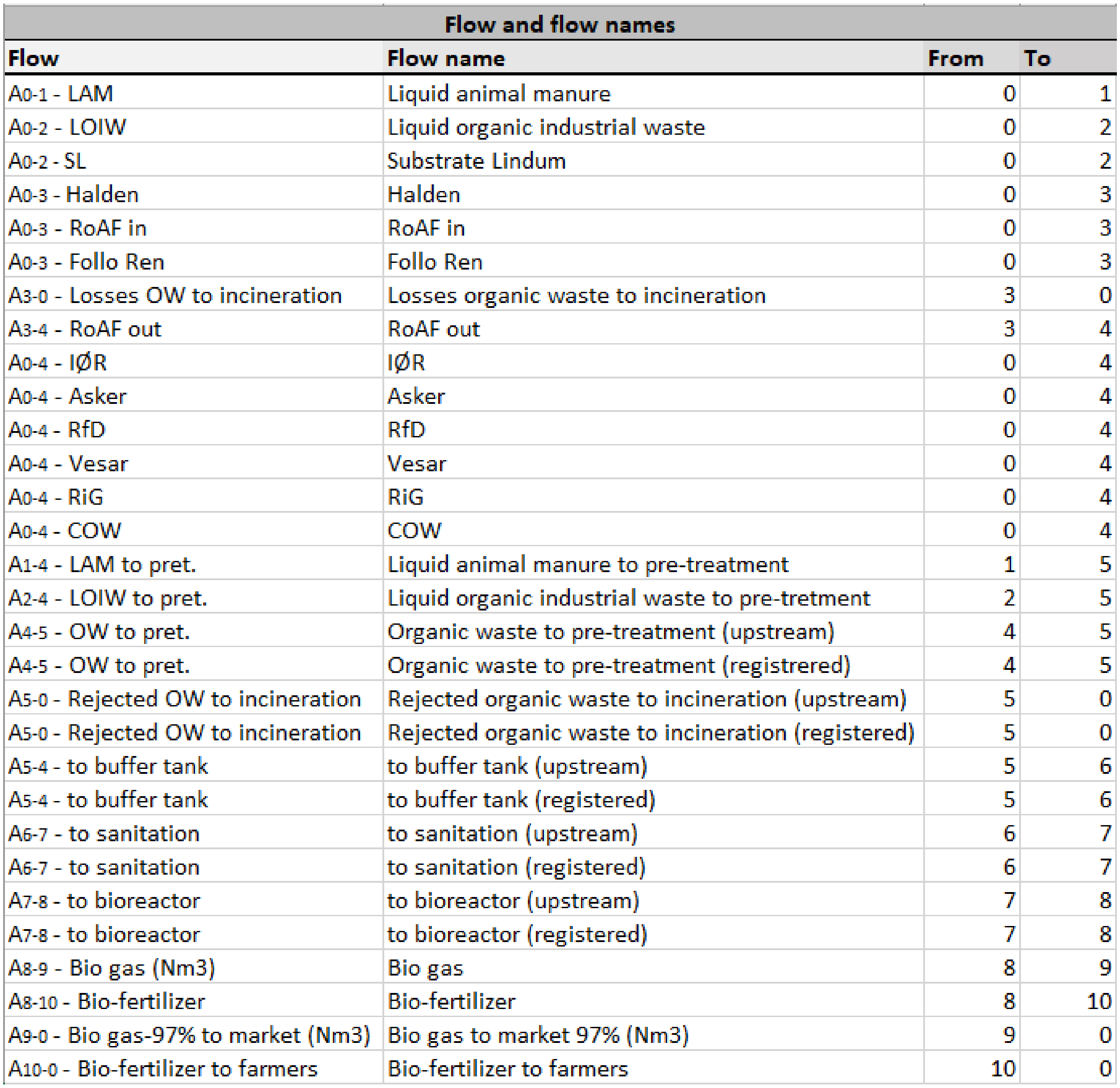


Parameter table

Parameter name	Value	Name	Unit	Reference
DM content LAM	5 %	ka01	DM/ton	Sørby 2015b(Hegg, 2015)
DM content LOIW	7 %	ka02a	DM/ton	Assumed: based on Carlsson & Uldal 2009
DM content Substrate Lindum	12 %	ka02b	DM/ton	Hegg, 2019
RoAF sorting facility loss ratio	19 %	ka30	WW/ton	Skovly, 2019
DM content OHW	33 %	ka04a	DM/ton	Sørby 2015b(Hegg, 2015)
DM content COW	33 %	ka04b	DM/ton	Sørby 2015b(Hegg, 2015)
DM content rejected OW	40 %	ka50a	DM/ton	Hegg, 2019
Rejected OW ratio	0,2	ka50b	WW/ton	Hegg, 2019
DM content substrate	13 %	ka56a	DM/ton	Hegg, 2019
DM content bio-fertilizer	5 %	ka810a	DM/ton	Hegg, 2019
Foreign objects substrate > 4 mm	0,03 %	ka56b	DM/ton	Greve Biogass, 2017
Plastics in substrate > 4 mm	78,3 %	ka56c	DM/ton	Greve Biogass, 2017
Foreign objects bio-fertilizer > 4 mm	0,09 %	ka810b	DM/ton	Greve Biogass, 2017
Plastics in bio-fertilizer > 4 mm	96 %	ka810c	DM/ton	Greve Biogass, 2017
Forign objects substrate > 2 mm	9,4	ka56d	cm2/kg	Greve Biogass, 2017
Plastics in substrate > 2 mm	78,3 %	ka56e	WW/ton	Assumed: based on Greve Biogass, 2017
Foreign objects bio-fertilizer > 2 mm	8,5	ka810c	cm2/kg	Greve Biogass, 2017
Plastics in bio-fertilizer > 2 mm	96 %	ka810d	WW/ton	Assumed: based on Greve Biogass, 2017
bio gas to bio gas 97% conv. ratio	0,63	ka89	Nm3	Assumed: based on Nygård, 2018
w% plastics Halden	*0,85 %*	ka03a	WW/ton	Weighted avg., all suppliers
w% plastics RoAF in	0,88 %	kao3c	WW/ton	Weighted avg., RoAF -16, -18 and 2019
w% plastics Follo Ren	*0,85 %*	ka03e	WW/ton	Weighted avg., all suppliers
w% plastics RoAF out	*0,87 %*	ka34	WW/ton	Weighted avg., suppliers to RoAF
w% plastics IØR	*0,85 %*	ka04c	WW/ton	Weighted avg., all suppliers
w% plastics Asker	0,68 %	ka04d	WW/ton	Pick-analysis, Asker 2018
w% plastics RfD	1,70 %	ka04e	WW/ton	Pick-analysis, RfD 2018
w% plastics Vesar	0,40 %	ka04f	WW/ton	Pick-analysis, Vesar 2018
w% plastics RiG	0,30 %	ka04g	WW/ton	Pick-analysis, RiG 2017
w% plastics COW	11,50 %	ka04h	WW/ton	Greve Biogass, 2017
w% OW of municipal waste Halden	28,28 %	ka03b	WW/ton	Edvardsen, 2019
w% OW of municipal waste RoAF	-	ka03d	WW/ton	-
w% OW of municipal waste Follo Ren	-	ka03f	WW/ton	-

Table 3.5: Parameters for process model calculations.

Secondly, a presentation of the flows and flow names is presented.



Flow and flow names

Flow	Flow name	From	To
A0-1 - LAM	Liquid animal manure	0	1
A0-2 - LOIW	Liquid organic industrial waste	0	2
A0-2 - SL	Substrate Lindum	0	2
A0-3 - Halden	Halden	0	3
A0-3 - RoAF in	RoAF in	0	3
A0-3 - Follo Ren	Follo Ren	0	3
A3-0 - Losses OW to incineration	Losses organic waste to incineration	3	0
A3-4 - RoAF out	RoAF out	3	4
A0-4 - IØR	IØR	0	4
A0-4 - Asker	Asker	0	4
A0-4 - RfD	RfD	0	4
A0-4 - Vesar	Vesar	0	4
A0-4 - RiG	RiG	0	4
A0-4 - COW	COW	0	4
A1-4 - LAM to pret.	Liquid animal manure to pre-treatment	1	5
A2-4 - LOIW to pret.	Liquid organic industrial waste to pre-tretment	2	5
A4-5 - OW to pret.	Organic waste to pre-treatment (upstream)	4	5
A4-5 - OW to pret.	Organic waste to pre-treatment (registrered)	4	5
A5-0 - Rejected OW to incineration	Rejected organic waste to incineration (upstream)	5	0
A5-0 - Rejected OW to incineration	Rejected organic waste to incineration (registered)	5	0
A5-4 - to buffer tank	to buffer tank (upstream)	5	6
A5-4 - to buffer tank	to buffer tank (registered)	5	6
A6-7 - to sanitation	to sanitation (upstream)	6	7
A6-7 - to sanitation	to sanitation (registered)	6	7
A7-8 - to bioreactor	to bioreactor (upstream)	7	8
A7-8 - to bioreactor	to bioreactor (registered)	7	8
A8-9 - Bio gas (Nm3)	Bio gas	8	9
A8-10 - Bio-fertilizer	Bio-fertilizer	8	10
A9-0 - Bio gas-97% to market (Nm3)	Bio gas to market 97% (Nm3)	9	0
A10-0 - Bio-fertilizer to farmers	Bio-fertilizer to farmers	10	0

Table 3.6: Model flows and flow names.

The parameters, given, assumed, or estimated, have been multiplied with the different given, assumed, or estimated flow values to form the different flows in the aforementioned layers. The parameters assumed are interpreted from figures and tables given while estimated values are estimated from weighted average based on data from reviewed studies and analyses.

Thirdly, the process model is presented. The blue dotted lines show the systemic boundaries of our model while the green dotted lines indicate the different sections of our model (i.e., all flows and processes upstream for DMF, the flows and processes within DMF, and the flows downstream of DMF).

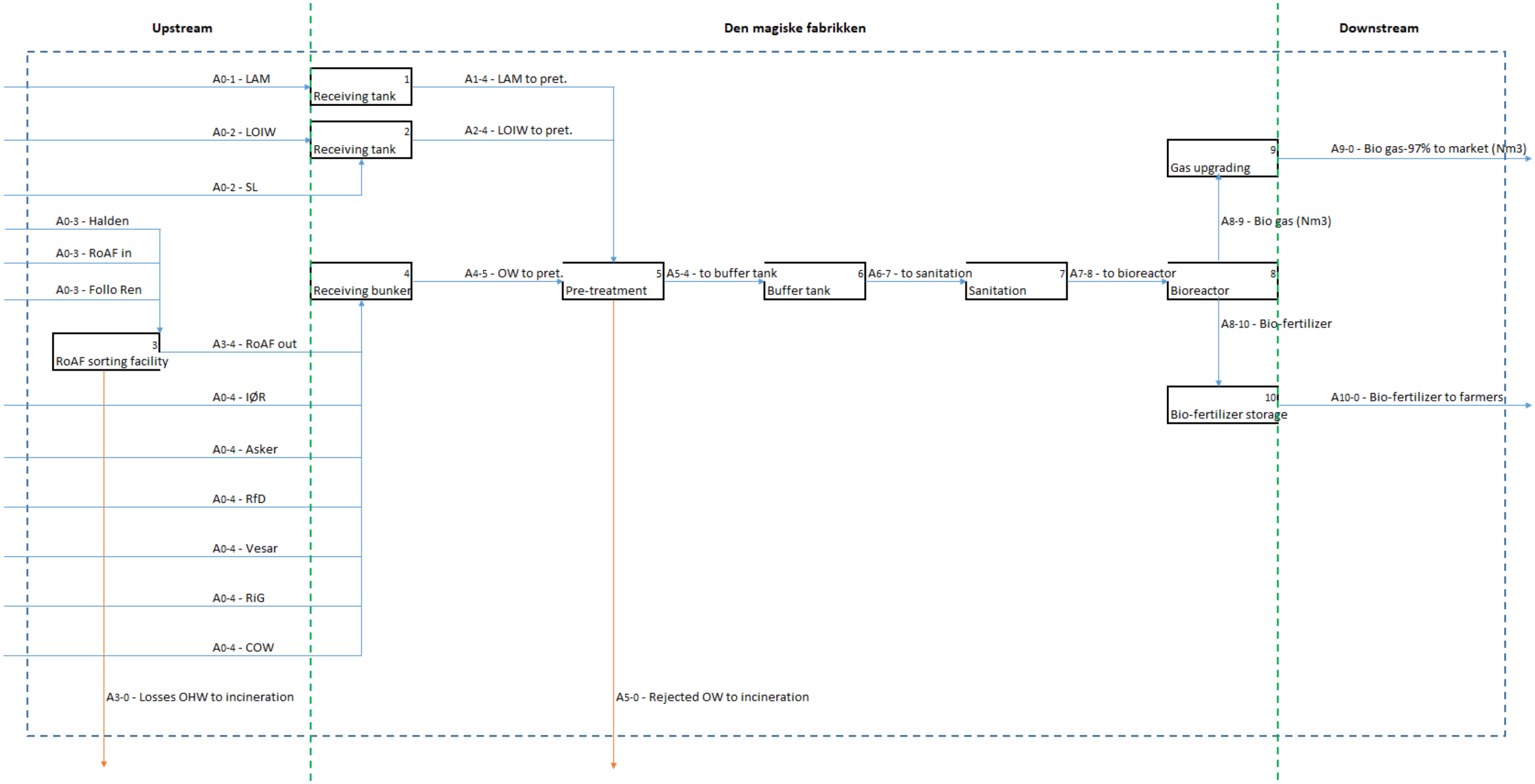


Figure 3.2: Process model.

3.4 MFA, quantifications, scenarios, uncertainty and sensitivity

This subchapter contains an explanation of the MFA, various quantifications and calculations, scenario descriptions, and the uncertainty and sensitivity analyses conducted for this paper.

Material Flow Analysis

MFA is an analytical method used to quantify material and product flows across different industrial sectors or ecosystems, within the defined system. Elementary to perform an MFA is to define the system, its boundaries, and details and the application of mass balance to reveal possible inconsistencies and errors throughout the system. An MFA is especially applicable to track specific materials or substances across different process layers/sectors. In our case, the level of plastics entering DMF in various forms from upstream sources which are further distributed downstream of DMF as plastic residue in bio-fertilizer.

Quantification of plastics entering DMF

One of the purposes of this study is to find the reduction potential of plastic residue in bio-fertilizer. By quantifying the amount of plastic entering DMF from the different upstream sources, this study aims to find feasible and sustainable solutions to reduce the level of plastic residue in bio-fertilizer. Below follows a presentation for quantifying the amount of plastics entering DMF in the form of plastic waste bags, incorrectly sorted plastics, and plastic packaging in COW.

This study has quantified the amount of plastic waste bags used for the collection of OHW (i.e., the amount of plastics entering DMF in the form of plastic waste bags per year). Either the supplier of OHW have provided the number of plastic waste bags used by each household per week, or the necessary data for calculating the number of plastic waste bags used by each household per week have been provided (i.e., quantity of plastic waste bags distributed to all households per year). Both approaches have successfully provided enough data to calculate the amount of plastic waste bags entering DMF per year. The factor ”number of plastic waste bags used by each household per week” hereby called ”bags per week” was crucial for calculating the annual amount of plastic in the form of plastic waste bags entering DMF from each supplier of OHW. A loss factor of 2,5 % for all plastic waste bags entering the RoAFs ESAR facility have been added to the results. The following formulas have been utilized to calculate the amount of plastic waste bags:

$$\mathit{number\ of\ bags} = \frac{\mathit{quantity\ of\ plastic\ bags\ distributed}}{\dfrac{\mathit{number\ of\ households}}{\dfrac{\mathit{weeks\ per\ year}}{\mathit{weight\ per\ bag}}}}$$

$$\mathit{annual\ plastic\ waste\ bags\ weight} = \mathit{number\ of\ bags} * \mathit{number\ of\ households} * \mathit{weight\ per\ bag} * \mathit{weeks\ per\ year}$$

The amount of plastics entering DMF as incorrectly sorted plastics have been derived from the pick-analyses and the mass of OHW delivered by each supplier. Specifically, the pick-analyses provided us with the composition of the OHW bags and their respective fractions in WW. The mass of OHW delivered by each supplier per upstream analysis differentiated from the registered mass at DMF, however, for our calculations we have utilized the values from the upstream analysis. The level of incorrectly sorted plastics ranges from 0,3 w% to 1,7 w% of OHW with a weighted average of 0,85 w%. To calculate the level of incorrectly sorted plastics exiting the ESAR facility, the weighted average (0,86w%) for RoAF, Follo, and Halden were used.

$$\begin{gathered} annual\ incorrectly\ sorted\ plastic\ weight \\ = \\ weight\ organic\ household\ waste * plastic\ fraction\ of\ organic\ household\ waste \end{gathered}$$

The amount of plastics entering DMF through COW as plastic packaging was derived from the study conducted by “Greve Biogass” in 2017, which showed level of foreign object as high as 17 w% while plastics constitute 11,5 w% of all COW delivered to DMF. Catering waste was also assessed, were plastics are constituting 8,3 w% of all catering waste. The annual amount of plastic entering DMF through COW was calculated in the following way:

$$\begin{gathered} annual\ plastic\ packaging\ weight \\ = \\ weight\ commercial\ organic\ waste * plastic\ fraction\ of\ commercial\ organic\ waste \end{gathered}$$

Scenarios

What we aim for is the feasible reduction potential of plastic residue in bio-fertilizer with the following measures/scenarios. For detailed assessments regarding the scenarios, see chapter 5.

Base scenario

The base scenario is based on the current practice and level of plastic entering DMF and the corresponding values of plastic residue in bio-fertilizer in 2018.

Scenario 1

A feasible replacement of PE waste bags with adapted alternative waste bags for most suppliers, and continued usage of PE waste bags for RoAF, Follo Ren, and Halden. For this scenario, plastic residue originating from bio bags (Mater-Bi) are neglected.

Scenario 2

Incorrectly sorted plastics are reduced to a minimum for all suppliers of OHW (i.e., aiming for the feasible plastic residue level similar to Vesar and RiG combined, 0,35 w% of OHW).

Scenario 3

Tougher demands/requirements for suppliers of COW, i.e. delivery of COW free of plastic packaging/pre-sorting of COW. Reduction of w% plastic packaging from 11,5 to 2,5, accounting for unique events requiring suppliers to deliver COW unsorted.

Scenario 4

Combining all three scenarios with the addition of adapted post-treatment like FRP and additional composting of dry fraction if bio bags are utilized.

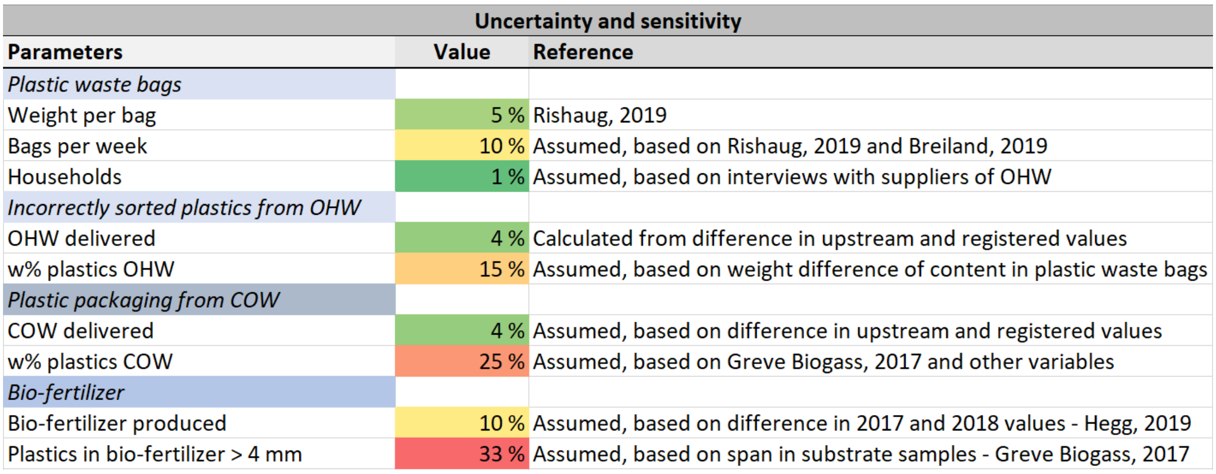
Uncertainty and sensitivity

To assess and measure the sensitivity of the parameters used (i.e., changing the input value to measure which variable affects the output value the most), the method of Sensitivity Ratio (SR) was utilized. SR is calculated in the following way:

$$SR \ = (\Delta R/R0)/(\Delta P/P0)$$

R_0 is the result value before changing the parameter value and ΔR the change in the final value after changing parameter value, P_0 and ΔP are the equivalents for the parameter value. High SR value indicates that the actual parameter affects the result notably. We don't wish to have high uncertainty for the input data for these variables. Large uncertainty in a variable that has a low SR value is not so critical. For detailed calculations see Appendix A.2.

Table 3.7 shows the parameter values used in the assessment which are based on assumptions for this paper. Green and light green equals small, yellow equals medium, while orange and red equals high uncertainties.



Uncertainty and sensitivity		
Parameters	**Value**	**Reference**
Plastic waste bags		
Weight per bag	5 %	Rishaug, 2019
Bags per week	10 %	Assumed, based on Rishaug, 2019 and Breiland, 2019
Households	1 %	Assumed, based on interviews with suppliers of OHW
Incorrectly sorted plastics from OHW		
OHW delivered	4 %	Calculated from difference in upstream and registered values
w% plastics OHW	15 %	Assumed, based on weight difference of content in plastic waste bags
Plastic packaging from COW		
COW delivered	4 %	Assumed, based on difference in upstream and registered values
w% plastics COW	25 %	Assumed, based on Greve Biogass, 2017 and other variables
Bio-fertilizer		
Bio-fertilizer produced	10 %	Assumed, based on difference in 2017 and 2018 values - Hegg, 2019
Plastics in bio-fertilizer > 4 mm	33 %	Assumed, based on span in substrate samples - Greve Biogass, 2017

Table 3.7: Uncertainties and sensitivity parameters.

The producers of plastic waste bags accept 5% variations in the thickness and weight of their plastic waste bags. Hence, the uncertainty for “weight per bag” has been set to 5%.

As proven by Breiland (2019) in Chapter 3.2.1, 90% of the green PE waste bags distributed to the households in RiG are utilized for the collection of OHW. The remaining 10% are utilized for other purposes within the households. Hence, the “bags per week” parameter has an uncertainty level of 10%.

Due to relocations and delays in municipal statistics, a small variation in the number of households is expected. Hence, the uncertainty for “households” was set to 1%.

The uncertainty for “OHW delivered” was set to 4%, as the values from the upstream analysis compared to the registered weight at DMF variates by 4%.

“w% plastics OHW” may vary with as much as 15%, considering fluctuations in many factors responsible for determining w% plastics in OHW. Hence, the uncertainty level is set to 15%.

The uncertainty for “COW delivered” is assumed the same as “OHW delivered” as the values from the upstream analysis compared to the registered weight at DMF variates by 4%.

“w% plastics COW” has an assumed uncertainty of 25%. Many factors determine this huge uncertainty, which requires a complementary discussion which is provided in 5.1.

When comparing levels of bio-fertilizer produced in 2017 and 2018, a 10 % difference is observed. We want to account for fluctuations in this parameter. Hence, the uncertainty level for “bio-fertilizer produced” is set to 10%.

“Plastics in bio-fertilizer > 4 mm” has the highest uncertainty-33% due to inconsistent sampling of plastic residue in substrate and bio-fertilizer. The level of plastic residue in bio-fertilizer is based on a single sample while the level of plastic residue in the substrate is based on four samples with a variation of 33% from the mean value of 0,3% of DM. For this reason, the corresponding level of plastic residue in bio-fertilizer may vary accordingly.

4 Results

4.2 Process model and MFA results

The process model and the MFA results for the base scenario of 2018 will be presented in the following subchapter. Figure 4.1 will display the flows in the wet weight layer, figure 4.2 the flows in the dry matter layer and figure 4.3 the flows in the plastic weight layer. For a complete overview of all flow values in all layers with references, see appendix A.4. Lastly the results for the sensitivity analysis will be presented in table 4.6.

For the following three figures displaying the results from the MFA, a further explanation is required regarding the terminology “upstream analysis” and “registered”. All layers will show two parallel values between process 5 and 8, “Pre-treatment” and “Bioreactor”, and between process 4 and 8, “Receiving bunker” and “Bioreactor” in the WW and DM layer. The value in the upper row shows the weight based on calculations from the upstream analysis - the level of organic waste provided by suppliers. Because all waste trucks delivering organic waste to DMF must be weighed before and after delivery to register levels of organic waste, the value in the lower row shows the weight based on calculations from the registered weight–the level of organic waste registered on the scale outside of DMF.

To make room for the resulting figures in the following pages, the figure explanations for the resulting figures displaying the different layers will follow here:

Figure 4.1 shows the wet weight layer, where light gray cells show values based on calculations from the upstream analysis while dark gray cells show values based on calculations from the registered weight.

Figure 4.2 shows the dry matter layer, where light gray cells show values based on calculations from the upstream analysis while dark gray cells show values based on calculations from the registered weight. The flow A_{5-4} – to buffer tank appears unbalanced over “Pre-treatment” as DM in LAM and LOIW are not rejected.

Figure 4.3 shows the plastic weight layer, where light gray cells show values based on calculations from the upstream analysis while dark gray cells show values based on calculations from the registered weight. Blue cells are displaying the weight of incorrectly sorted plastics, green cells - the weight of plastic waste bags, orange cells–the total plastic weight from suppliers, red cells–the total mass of plastics entering DMF. The flows LAM and LOIW are assumed free of plastic residue while the contribution of flow A_{0-2} – SL of the total makes the level of plastic residue for this flow negligible, hence the blank cells. Regarding flow A_{5-0} – Rejected OW to incineration, these cells are blank because the level of plastic residue is impossible to determine by mass balance and from outdated pick-analysis. Flow A_{8-10} - Bio-fertilizer shows higher level of plastic than A_{7-8} - to bioreactor due to higher concentrations of plastic in bio-fertilizer.

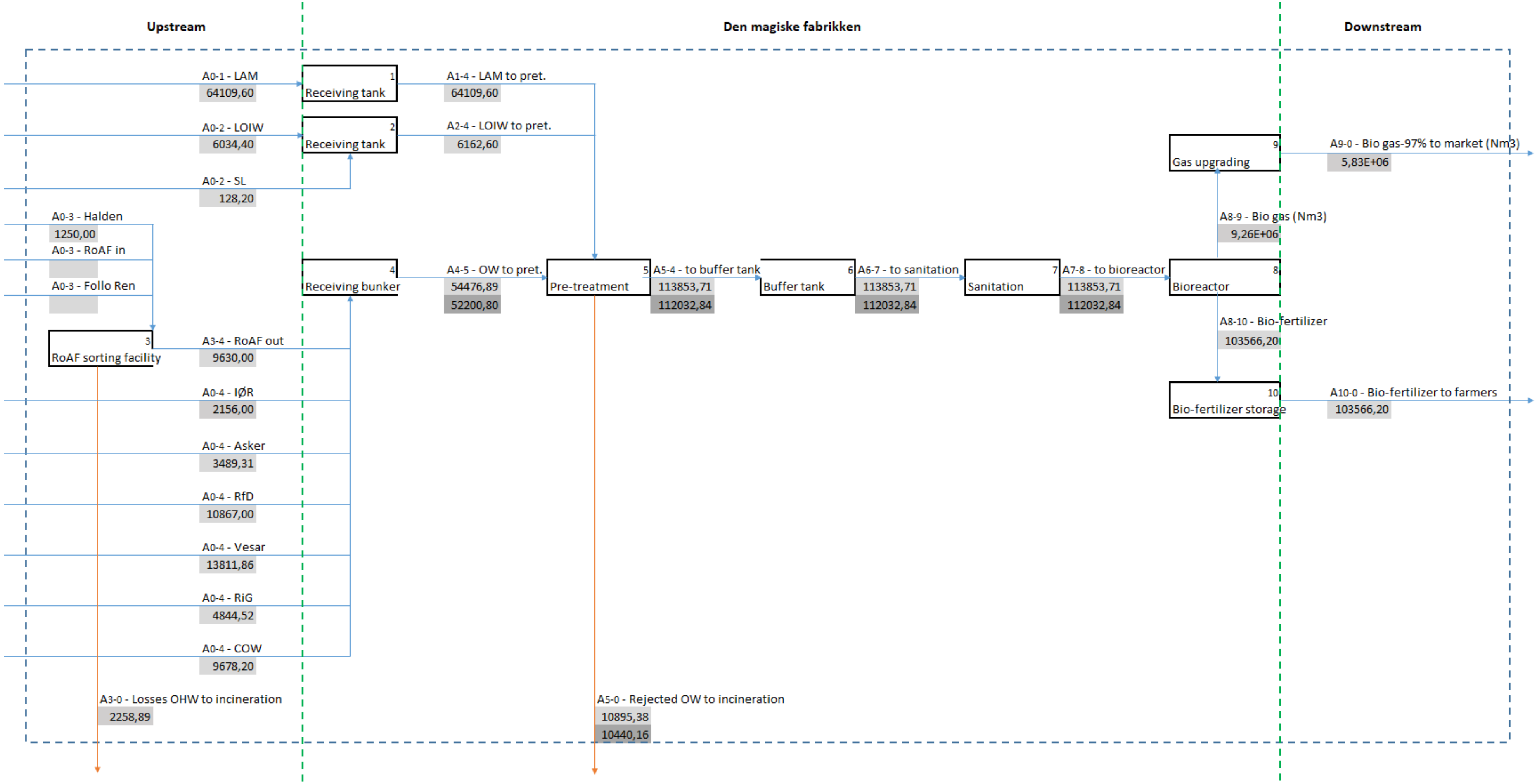


Figure 4.1: Wet weight layer.

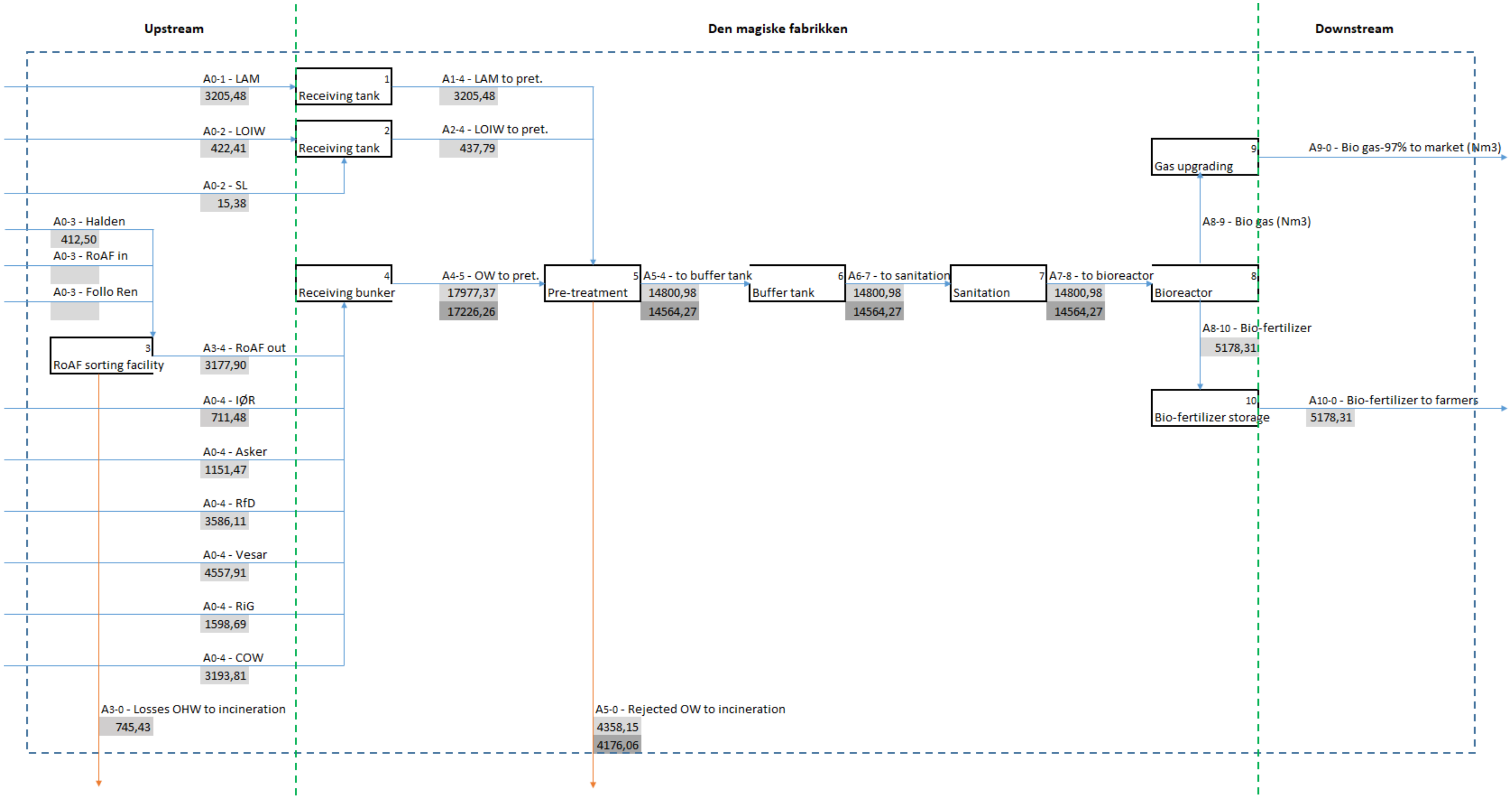


Figure 4.2: Dry matter layer.

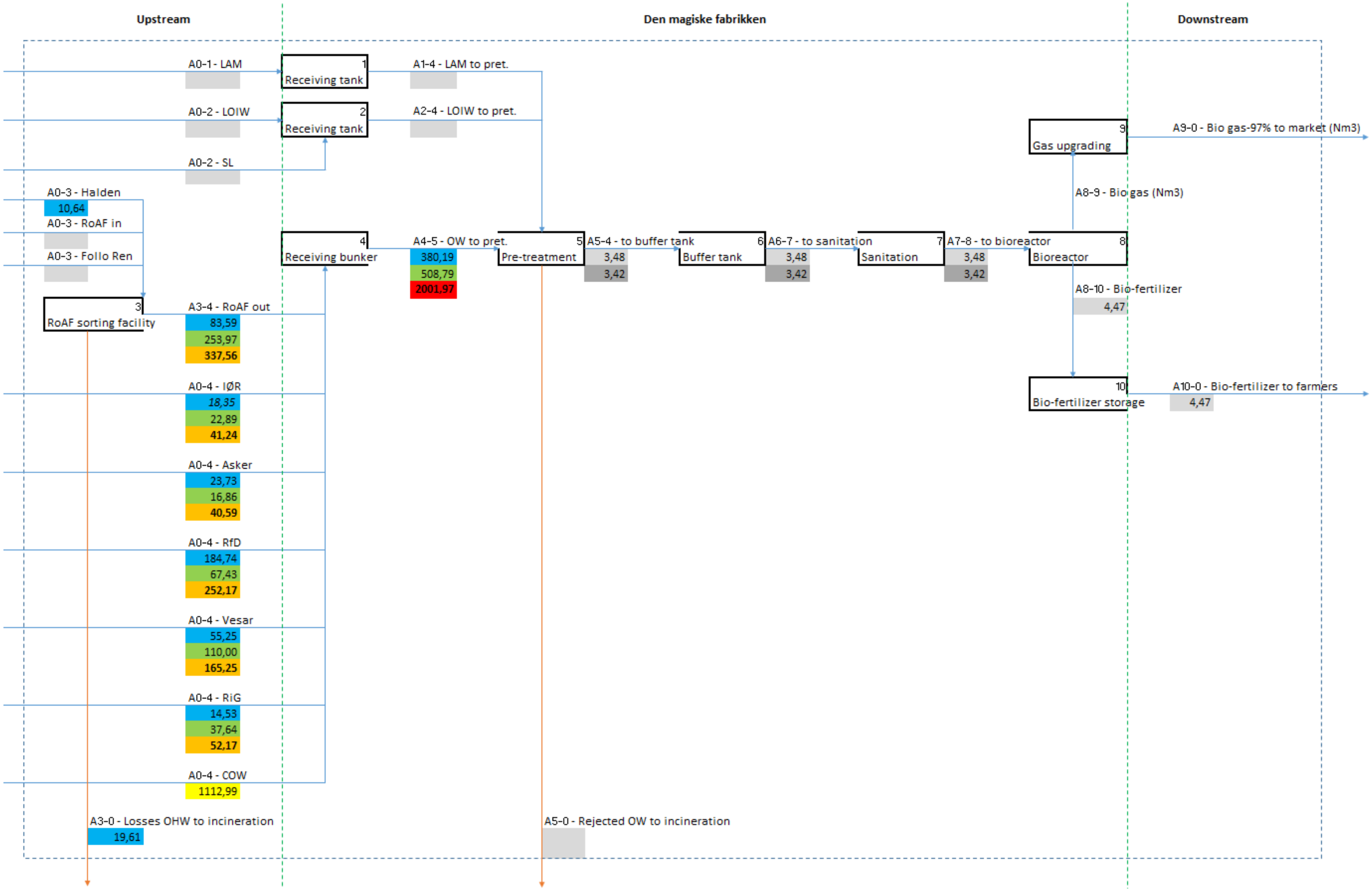
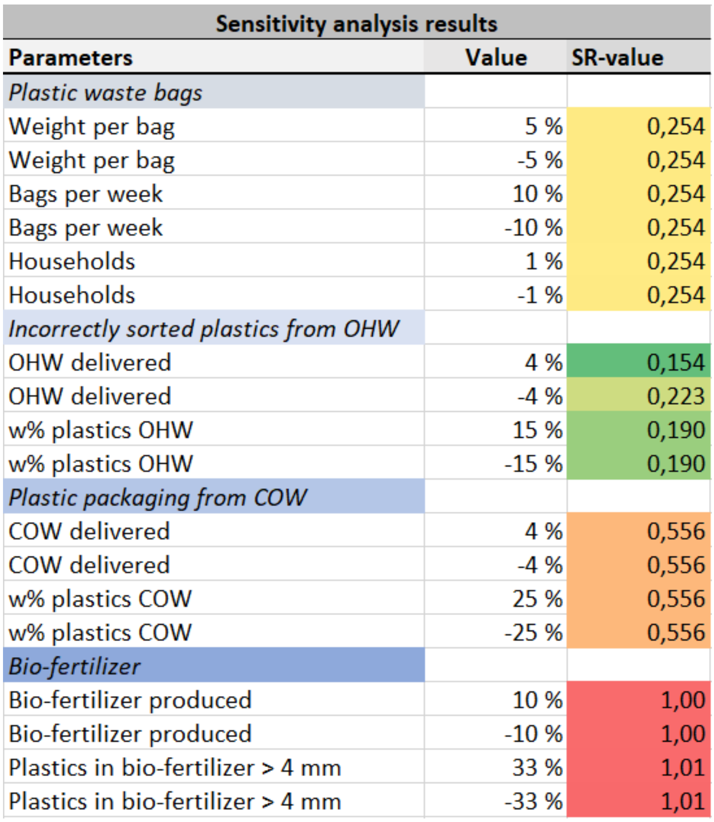


Figure 4.3: Plastic weight layer.

Table 4.6 shows the sensitivity analysis results displayed in SR-values. Green indicates small, yellow indicates medium, orange indicate high and red indicating 100% sensitivity.



Sensitivity analysis results

Parameters	Value	SR-value
Plastic waste bags		
Weight per bag	5 %	0,254
Weight per bag	-5 %	0,254
Bags per week	10 %	0,254
Bags per week	-10 %	0,254
Households	1 %	0,254
Households	-1 %	0,254
Incorrectly sorted plastics from OHW		
OHW delivered	4 %	0,154
OHW delivered	-4 %	0,223
w% plastics OHW	15 %	0,190
w% plastics OHW	-15 %	0,190
Plastic packaging from COW		
COW delivered	4 %	0,556
COW delivered	-4 %	0,556
w% plastics COW	25 %	0,556
w% plastics COW	-25 %	0,556
Bio-fertilizer		
Bio-fertilizer produced	10 %	1,00
Bio-fertilizer produced	-10 %	1,00
Plastics in bio-fertilizer > 4 mm	33 %	1,01
Plastics in bio-fertilizer > 4 mm	-33 %	1,01

Table 4.6: Sensitivity analysis results.

4.1 Upstream analysis results

In the following subchapter the results from the upstream analysis, pick-analyses, and scenario analysis will be presented.

Table 4.1 shows the total weight of plastic waste bags entering DMF in 2018 in DM tons, as calculated from "annual plastic weight bag weight" in Chapter 3.4. * = calculated from the mean value of "bags per week. ** = calculated with a correction factor of 2,5%, accounting for assumed losses through RoAFs ESAR facility.

	Plastic waste bags					
	Inhabitants	**Households**	**Bags per week**	**Weeks per year**	**Weight per bag(kg)**	**Plastic weight(tons)**
Halden	31177	12990	1,69	52	0,0089	**9,91
Follo	113841	43000	3	52	0,0122	**79,79
RoAF	203135	90000	3	52	0,012	**164,27
IØR	51709	23291	2,7	52	0,007	22,89
Asker	61523	21750	*2,66	52	0,0056	16,86
RfD	202111	88820	2	52	0,0073	67,43
Vesar	234471	112000	3,34	52	0,00565	110,00
RiG	107287	32412	2,9	52	0,0077	37,64
Total	**1005254**	**424263**				**508,79**

Table 4.1: Plastic waste bags entering DMF in 2018.

Table 4.2 shows the total weight of incorrectly sorted plastics entering DMF in 2018, as calculated from "annual incorrectly sorted plastic weight" in Chapter 3.4. Unknown whether weight is given in WW tons or DM tons.

	Incorrectly sorted plastics in OHW			
	Total FO	**% plastics**	**OHW delivered to DMF in 2018 (tons)**	**Incorrectly sorted plastics (tons)**
Halden	5,20 %	*0,85 %*	-	-
Follo	2,50 %	*0,85 %*	-	-
RoAF	3,30 %	0,88 %	9630,00	83,59
IØR	-	*0,85 %*	2156,00	18,35
Asker	3,90 %	0,68 %	3489,31	23,73
RfD	8,30 %	1,70 %	10867,00	184,74
Vesar	2,20 %	0,40 %	13811,86	55,25
RIG	2,80 %	0,30 %	4844,52	14,53
Total			**44798,69**	**380,19**

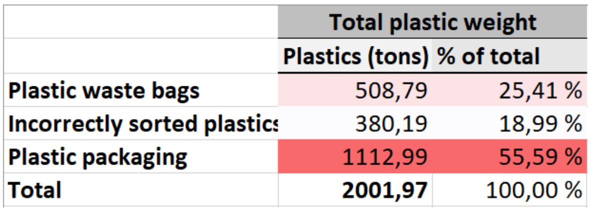
Table 4.2: Incorrectly sorted plastics from OHW entering DMF in 2018.

Table 4.3 shows the total weight of plastic packaging entering DMF in 2018, as calculated from "annual plastic packaging weight" in Chapter 3.4. Unknown whether weight is given in WW tons or DM tons.

	Plastic packaging in COW			
	Total FO	**% plastics**	**COW delivered to DMF in 2018 (tons)**	**Plastic packaging (tons)**
COW	17 %	11,50 %	9678,20	**1112,99**

Table 4.3: Plastic packaging from COW entering DMF in 2018.

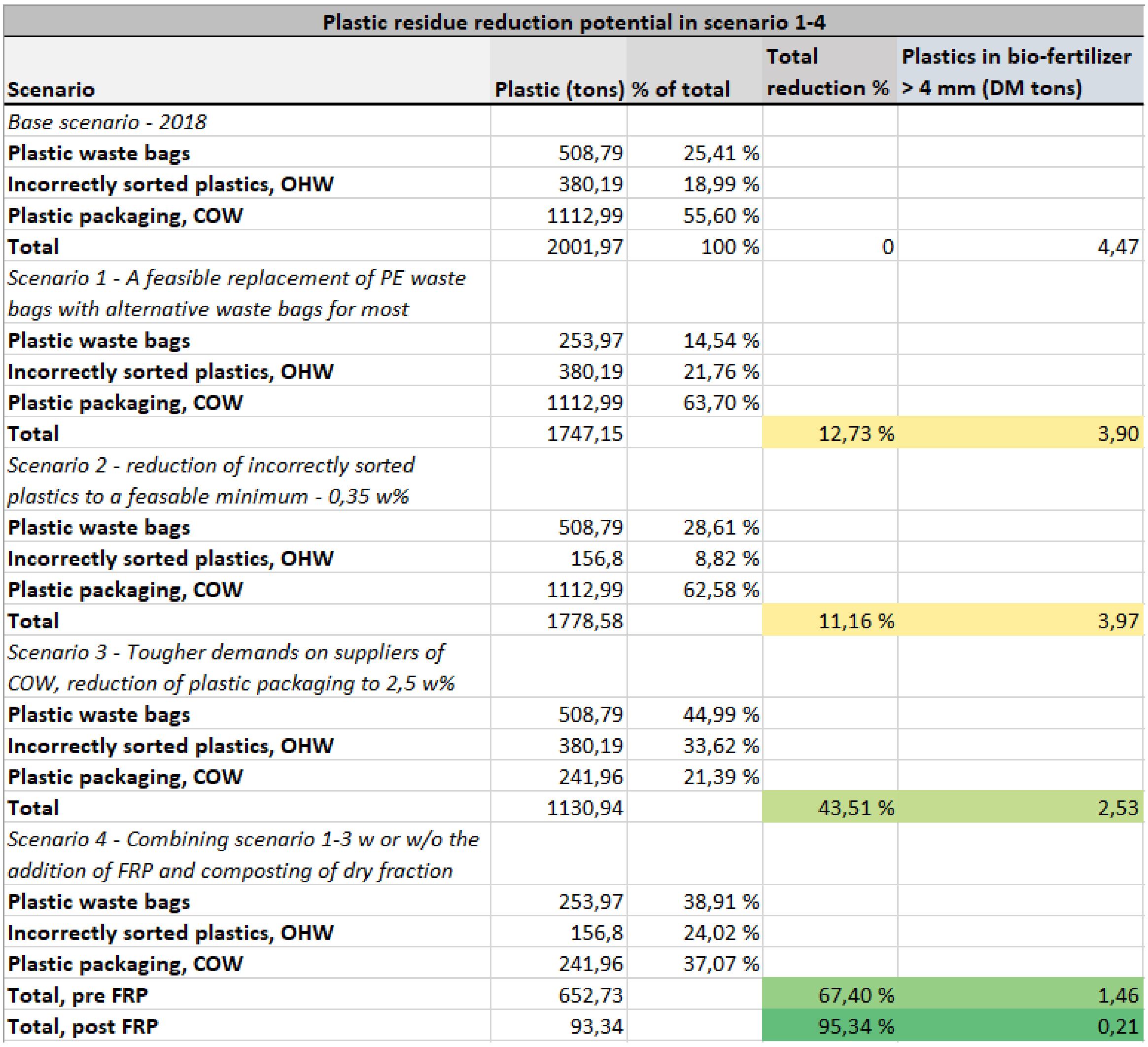
Table 4.4 shows the total plastic weight to DMF in 2018 from upstream sources. Unknown whether total weight is given in WW tons or DM tons. The intensity of redness indicate the proportions of total plastic from the various sources.



	Total plastic weight	
	Plastics (tons)	**% of total**
Plastic waste bags	508,79	25,41 %
Incorrectly sorted plastics	380,19	18,99 %
Plastic packaging	1112,99	55,59 %
Total	**2001,97**	100,00 %

Table 4.4: Total plastic weight by source to DMF in 2018.

Table 4.5 shows the plastic residue reduction potential in scenarios 1-4. The reduction potential is displayed in percentage reduction of the total weight of plastics entering DMF from the base scenario and the corresponding level of plastic residue > 4 mm in bio-fertilizer in DM tons. Yellow represents small, yellow-green represents medium and darker green represents large plastic residue reduction.



Plastic residue reduction potential in scenario 1-4				
Scenario	**Plastic (tons)**	**% of total**	**Total reduction %**	**Plastics in bio-fertilizer > 4 mm (DM tons)**
Base scenario - 2018				
Plastic waste bags	508,79	25,41 %		
Incorrectly sorted plastics, OHW	380,19	18,99 %		
Plastic packaging, COW	1112,99	55,60 %		
Total	2001,97	100 %	0	4,47
Scenario 1 - A feasible replacement of PE waste bags with alternative waste bags for most				
Plastic waste bags	253,97	14,54 %		
Incorrectly sorted plastics, OHW	380,19	21,76 %		
Plastic packaging, COW	1112,99	63,70 %		
Total	1747,15		12,73 %	3,90
Scenario 2 - reduction of incorrectly sorted plastics to a feasable minimum - 0,35 w%				
Plastic waste bags	508,79	28,61 %		
Incorrectly sorted plastics, OHW	156,8	8,82 %		
Plastic packaging, COW	1112,99	62,58 %		
Total	1778,58		11,16 %	3,97
Scenario 3 - Tougher demands on suppliers of COW, reduction of plastic packaging to 2,5 w%				
Plastic waste bags	508,79	44,99 %		
Incorrectly sorted plastics, OHW	380,19	33,62 %		
Plastic packaging, COW	241,96	21,39 %		
Total	1130,94		43,51 %	2,53
Scenario 4 - Combining scenario 1-3 w or w/o the addition of FRP and composting of dry fraction				
Plastic waste bags	253,97	38,91 %		
Incorrectly sorted plastics, OHW	156,8	24,02 %		
Plastic packaging, COW	241,96	37,07 %		
Total, pre FRP	652,73		67,40 %	1,46
Total, post FRP	93,34		95,34 %	0,21

Table 4.5: Plastic residue reduction in scenarios 1-4.

5 Discussion

5.1 Main findings

Results

In the results presented above it was found that large amounts of plastics are entering DMF from various upstream sources, some persisting through the facility ending up as plastic residue in bio-fertilizer. Around 2000 tons of plastics entered DMF in the form of plastic waste bags, incorrectly sorted waste, and plastic packaging while 4,47 tons (DM) of plastic residue > 4 mm was estimated to end up in bio-fertilizer. Although the latter number has a high uncertainly it reveals that around 0,2% of plastics from upstream sources ending up as plastic residue in bio-fertilizer. For further discussion regarding plastic residue in bio-fertilizer, see Chapter 5.3.

It has been estimated in the results that 508,8 tons of plastic enter DMF as plastic waste bags in 2018. This estimation is very high, as it assumes all plastic waste bags distributed to households are utilized for the collection of OHW. This assumption has been described as a source of error from several holds within the solid waste management sector and was confirmed by Breiland (2019) which proved that 10% of plastic waste bags distributed to households are not utilized for the collection of OHW. The return ratio of 90% can be explained by the distribution practice of plastic waste bags to households. All households receive a default supply of 100 plastic waste bags each year from suppliers. If necessary and regardless of real demand, then a default resupply of 50 pieces are delivered to households. For this reason, the supply may surpass the demand, hence a reduced return ratio. For this reason, a conservative estimate for amount of plastic waste bags is more realistic compared to the high estimate. When including the conservative estimate in our calculations, the real amount of plastic waste bags entering DMF is likely to be 457,9 tons. Hence, 457,9-508,8 tons (DM) of plastics entered DMF as plastic waste bags in 2018.

Furthermore, is has been estimated that 380,2 tons of plastic entered DMF as incorrectly sorted plastics in OHW in 2018. For this type of plastics, an uncertainty of 15% is assumed, as w% incorrectly sorted plastics fluctuates by year, supplier and by mean weight of content of OHW in the plastic waste bag which percentage of plastics are estimated from. Including the low and high variation in our calculations, the level of incorrectly sorted plastics entered DMF in 2018 may range between 323,2-437,2 tons.

Finally, 1113 tons of plastics in the form of plastic packaging has been estimated to enter DMF in 2018, which amounts to around 55% of all plastics. From Greve Biogass (2017), four independent pick-analyses was conducted of COW originating from grocery stores, offices and the likely, showing that the mean level of plastics constitutes 11,5% of COW. The w% of 11,5 only provided us with a clue because COW is permeated by continuous inconsistency regarding suppliers, content, unpredictable and unique events and so on. Unique events are incidents that require suppliers to dispose of large batches of completely unsorted COW, containing higher levels of plastics because both plastic packaging and plastic wrapping are delivered unsorted with the COW. Considering the inconsistencies and unique events, an uncertainty of 25% are likely to apply for w% plastics in COW. Hence, the w% plastics in COW may range from 8,6-14,4%, corresponding with 834,7-1391,2 tons of plastics. Given that suppliers incrementally strive toward material effectiveness, confirmed by Nortura Forbrukersenter (2020), and unique events are less common, the realistic estimate is likely to be in the low range (i.e., 834,7-1113 tons of plastics entered DMF in the form of plastic packaging in 2018).

The relatively small proportion of organic waste delivered as COW, constitute per results around 55% of all plastics entering DMF. Because the suppliers are not required to conduct pre-sorting, COW is *often* delivered entirely in its original plastic packaging.
An important assumption for this study is that the level of plastics entering DMF is correlated to the level of plastic residue in bio-fertilizer. However, there may not be a consistent correlation between the level of plastic packaging entering DMF and plastic residue in bio-fertilizer. From Hegg (2019), hard and in-moldable organic waste are rejected in separator while soft and moldable organic waste pass through the separator. This may also apply for plastics with the same characteristics, and as hard and less moldable plastics are utilized as plastic packaging for many grocery products delivered as COW to DMF, a larger share of plastic packaging may be rejected (i.e., not entering the bioreactor). Also, from Figure 2.3 and Figure 2.5 we mostly observe soft and moldable plastics in samples of bio-fertilizer, easily observable is plastic residue from plastic waste bags. These assumptions are not conclusive as we lack updated pick-analyses of the reject, but there may be a correlation.

In 2018, the real estimate revealed that between 1615,8 and 2059 tons of plastics entered DMF. The plastics constituted 3-3,8% (in WW) and 9-11,6% (in DM) of OHW and COW, and 1,3-1,7% (in WW) and 7.5-9.5% (in DM) of total organic waste delivered to DMF. Through pre-treatment, the amount of plastics was reduced to 0,2% of its original amount. In bio-fertilizer, that constituted 0,09% of DM and 0,004% of WW, respectively.

Sensitivity
For this study, sensitivity analysis was conducted because it was important to assess the degree of uncertainty and how it may affect the results. We conducted the analysis with several parameters for each source of plastic entering DMF, and for the bio-fertilizer exiting DMF. For “plastic waste bags”, all parameters considered gives the same medium SR-value, as all parameters are part of the same equation used to quantify the amount of plastic waste bags. Any change in the parameters for “incorrectly sorted waste” gives small SR-values, as this is the smallest share of plastics entering DMF. Thirdly, the sensitivity for the parameters in “plastic packaging” is high, as plastic packaging in COW constitute around 55% of all plastics entering DMF, any change of the parameters affects the result considerably. Finally, any change in the parameters for “bio-fertilizer” will affect the results 100%, hence an SR-value of 1 or greater will result.

Scenarios

One of the most important aspect of this study, next to quantifying the level of plastics entering DMF, has been to estimate the reduction potential of plastic residue in bio-fertilizer. This has been done by creating scenarios, by modeling the effects of implementing feasible measures either upstream or downstream of DMF.

For Scenario 1 we have replaced most PE waste bags with alternative waste bags. RoAF, Follo Ren and Halden have continued the collection practice with PE waste bags until further tests have been conducted to assess whether the Biodolomer F30 bags possesses mechanical properties to endure the handling both *before* and throughout the ESAR facility. The level of plastic residue originating from plastic waste bags can be reduced to near zero if the Biodolomer F30 bags are proven to be equally or more compatible with the ESAR facility, compared to the current practice of PE waste bags.

In Scenario 2 we modeled the impact on plastic residue if incorrectly sorted plastics are reduced to a minimum for all suppliers of OHW (i.e., aiming for the feasible plastic residue level similar to Vesar and Rig combined) (0,35 w% of OHW). It was assumed that the incorrect sorting of plastics will always persist to some degree. Hence, it is demanding to bring level of incorrectly sorted plastics to nearly zero, but it is proved to be reduced to feasible low levels by RiG and Vesar.

Scenario 3 concerns the plastic packaging entering DMF with COW. By imposing stricter demands on suppliers (i.e., pre-sorting of plastic packaging, and rewarding suppliers with economic benefits for complying), we assume a significant reduction potential in w% from COW can be achieved. The fictive w% of 2,5 includes potential deliveries of un-sorted COW during unique events at suppliers (i.e., fires, flooding and other incidents that require large batches of COW to be disposed of quickly).

Lastly, in Scenario 4, all measures are combined, showing a reduction potential of 67,4% and 95,3% pre and post adapted post-treatment. In this case, adapted post-treatment combines Fournier Rotary Press followed by composting of the dry fraction to degrade plastic waste bags and plastic packaging made from compostable and degradable plastics.

Summary of main findings

The 2000 tons of plastics entering DMF in 2018 was reduced to 0,2% of its original amount through pre-treatment. Thus, 4,47 tons (DM) of plastic residue in the form of plastics and microplastics entered terrestrial ecosystems through bio-fertilizer.

It was revelated that the biggest potential of reducing plastics from upstream sources was through pre-sorting of plastic packaging for COW, because this fraction of plastics constituted the biggest amount delivered in 2018. Further, any implementation of alternative waste bags adapted to the collection practice for the different suppliers and utilized in waste handling systems which enables aeration and ventilation during storage, can reduce the amount of plastics from upstream sources noteworthy.

Based on the interviews, enterprise visits, and the findings from Napper and Thompson (2019), waste bags made from Mater-Bi is regarded as environmentally safe because of its behavior in marine and open-air environments, if applied correctly. If bio-fertilizer containing plastic residue of Mater-Bi is spread on agricultural land, one must ensure that the plastic residue is not pushed into the ground, nor that the soil is turned, to allow for total disintegration of Mater-Bi in open-air environments. For any migration of plastic residue containing Mater-Bi from terrestrial ecosystems to aquatic ecosystems, a total biodegradation will occur. However, if one wants to completely remove all plastic residue of Mater-Bi in bio-fertilizer, additional composting of the dry fraction of the bio-fertilizer is recommended.

If alternative waste bags made from Biodolomer F30 or Ecocomp are utilized, no additional composting of the dry fraction of the bio-fertilizer is needed. Waste bags made from Biodolomer F30 in combination with Cellwood pre-treatment degrade within 30 days in bioreactors, and no visible plastic residue is observed from Biodolomer F30 in bio-fertilizer. For any remaining residue of Ecocomp, farmers and agricultural land is presented with an additional carbon source for plant growth.

5.2 Findings in relation to literature

Very few studies regarding plastic and microplastic sources to terrestrial ecosystems have been conducted, not to mention plastic residue in bio-fertilizer. Thus, sufficient literature was hard to obtain. However, the results from Weithmann et al. (2018) supported us with parallel findings regarding amount of MPPs found in composts and bio-fertilizers from aerobic and anaerobic process plants, with various organic input, and treatment. The general findings pointed to correlations between the composition of organic waste and degree of pre- and post-treatment with the amount of plastic residue in compost and bio-fertilizer. More specifically, bio-fertilizer made solely from COW contained 895 MPPs > 1 mm kg-1 (DM). That is 6-64 times the amount of MPPs found in the other compost and bio-fertilizers originating from other compositions of organic waste. This emphasizes the correlations in our study where the amount of plastics from plastic packaging in COW constitutes the majority of plastics entering DMF from upstream sources.

5.3 Strengths and weaknesses

Strengths

The main strength of this paper is the model. The model includes all suppliers of OHW with a complete and transparent data foundation for calculating the different mass layers. Furthermore, the model and its assumptions accounts for changes in flows and parameters as the sensitivity is consistently measurable throughout and across the sections in the model (i.e., any change in upstream value for any given layer is measurable in bio-fertilizer).

Weaknesses
One of the biggest weaknesses in this study was the researcher's ability to estimate the real level of plastic residue in bio-fertilizer. The main parameter used for calculating this value rests on one single sample with an uncertainty of 33%. This may also be illustrated in Figure 4.3 because the level of plastic is higher post bioreactor, compared to pre bioreactor. However, this can also be explained due to the level of DM is reduced through fermentation that concentrates non-degradable materials in the bio-fertilizer. Moreover, the parameter used to calculate the level of plastic residue in bio-fertilizer includes plastic pieces > 4 mm, leaving out plastic residue < 4 mm. To further exacerbate this weakness, FTIR, which is the current method to quantify and classify microplastic residue has a lower limit of 1 mm (Joner, 2019), which leaves out plastic residue < 1 mm. Hence, the real level of plastic residue which is assumed to correspond to the level of plastics entering DMF remains unknown.

Next to quantifying the level of plastic residue in bio-fertilizer, finding an accurate estimate of the amount of plastics entering DMF was difficult because many factors and parameters with uncertainties are included for this calculation. This may be a cause of errors, hence the establishment of a variable estimate.

Regarding the Fournier Rotary Press (FRP), the analysis conducted by Fagerheim (2019) established a potential to reduce plastic residue in bio-fertilizer by 85,7%, from a conservative estimate. However, the analysis conducted to establish that reduction potential was performed under conditions that may have caused room for errors. The time between sampling and weighting of the plastic residue may have caused an unnecessary drying of the samples, causing an inconsistency between the sampling of bio-fertilizer (wet weight) and plastic residue in bio-fertilizers (near dry weight). To account for potential uncertainties and errors in the lab, the new FRP plastic reduction level is reduced from 85,7% to 75%.

5.4 Implications regarding policy and future work

Throughout this study, several possible implications regarding policy and future work was identified. These implications can further and more accurately determine the level of plastics entering DMF from upstream sources and be utilized to assess the reduction potential of plastic residue in bio-fertilizer:

- To further solidify the mass balance over the process ”Pre-treatment” and determine the amount of plastics rejected in the separator, a pick-analysis for the rejected organic waste needs to be commenced.
- To reduce the level of plastic waste bags, tests regarding Biodolomor F30 bags compatibility with OHW collection practice for RoAF, Follo Ren and Halden must be completed.
- For suppliers choosing to continue the collection practice with PE waste bags, new bids to suppliers of plastic waste bags with demands of efficient plastic waste bags (i.e., maximum weight reduction of plastic waste bags).

- The behavior of bio bags made from Mater-Bi in soil must be established to further establish its compatibility for Nordic conditions (i.e., whether an accumulation of compostable plastics occurs in soils due to poor conditions for biodegradation).
- For other suppliers to reduce the level of incorrectly sorted plastics to a feasible minimum, a detailed study regarding the collection practice of RiG and Vesar must be established.
- Furthermore, pick-analysis or COW must be commenced, to more accurately determine the amount and types of plastics entering DMF.
- To suppliers of COW, a study of which measure(s) most efficiently reducing the level of plastic packaging entering DMF is preferable.
- Lastly, the level of plastic residue in bio-fertilizer must be established from multiple samples to reduce the level of uncertainty and to establish a more realistic estimate.

6 Conclusion

Based on the results of the present study, it was revealed that around 2000 tons of plastics entered DMF from upstream sources in 2018. 458-509 tons (DM) of plastics entered DMF in the form of plastic waste bags, whereas the lower range of the estimate is assumed more correct. This is due to the return ratio of plastic waste bags from households to collectors. Between 323 and 437 tons of plastics entered DMF as incorrectly sorted waste in OHW, and finally 835-1391 tons of plastic entered DMF as plastic packaging in COW, whereas the estimate of 835-1113 tons of plastics as plastic packaging are likely.

Further, it was estimated that the bio-fertilizer delivered to the market contained 4,47 tons (DM) of plastic residue > 4 mm. The amount of plastic and microplastic residue in bio-fertilizers has a high uncertainty of 33%. Hence, the real amount of plastic and microplastic residue > 4 mm found in bio-fertilizer produced by “Greve Biogass” may vary correspondingly.

The reduction potential of plastic residue in bio-fertilizer was estimated to be at least 67% by implementing measures upstream of DMF. Combining upstream measures with adapted post-treatment downstream of DMF, the FRP can further reduce the level of plastic residue by 75%, resulting in a cumulative reduction of 92%.

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8 Appendix

A.1 Population municipalities

Table A.1 showing population per Q4 in 2018 in all municipalities delivering OHW to DMF.

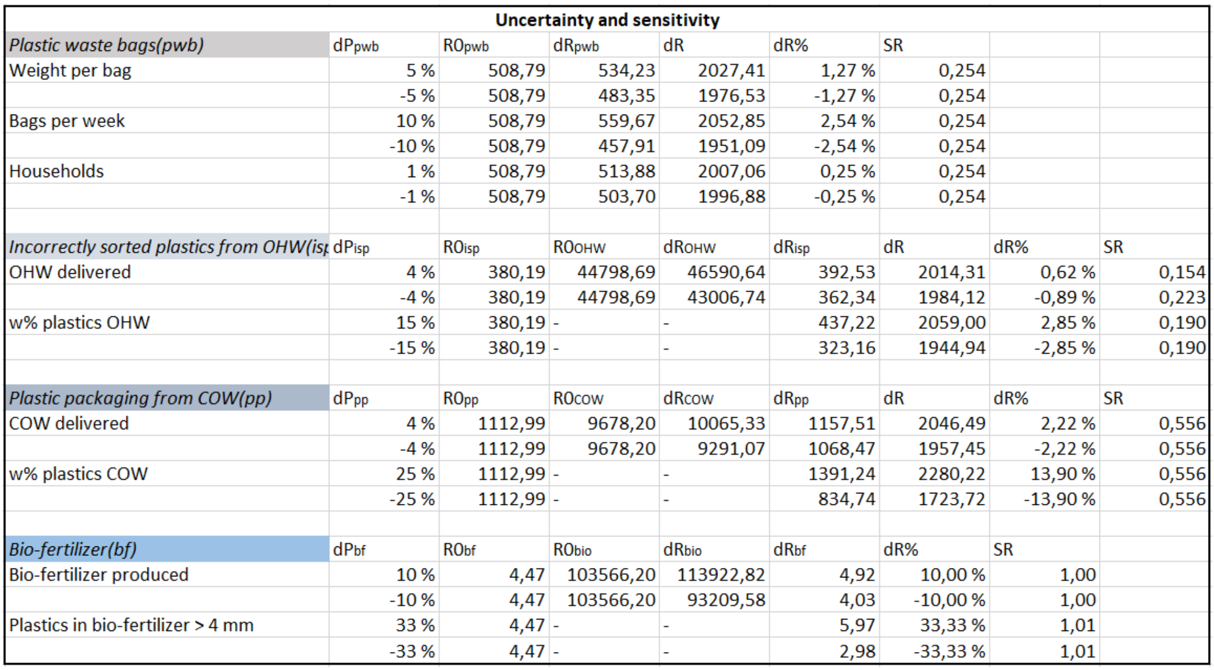
RoAF - Romerike avfallsforedling	
Sørum	18263
Fet	11842
Rælingen	18161
Enebakk	11026
Lørenskog	40106
Skredsmo	55652
Nittedal	24089
Gjerdrum	6823
Aurskog-Høland	16500
Rømskog	673
	203135
Follo Ren	
Nesodden	19488
Frogn	15761
Ås	20355
Oppegård	27394
Ski	30843
	113841
Halden kommune	
Halden	**31177**
IØR – Indre Østfold Renovasjon	
Askim	15865
Eidsberg	11424
Spydeberg	6042
Hobøl	5642
Marker	3592
Skiptvet	3797
Trøgstad	5347
	51709
Asker kommune	
Asker	**61523**
RfD – Renovasjonsselskapet for Drammensregionen	
Drammen	68933
Hurum	9521

Lier	26373
Modum	13980
Nedre Eiker	24963
Røyken	22635
Sande	9904
Svelvik	6685
Øvre Eiker	19117
	202111
Vesar – Avfallsselskapet i Vestfold	
Horten	27335
Holmestand	14347
Larvik	47107
Færder	26700
Sandefjord	63278
Tønsberg	45974
Re	9730
	234471
RiG – Renovasjon i Grenland	
Skien	54645
Porsgrunn	36224
Bamble	14089
Siljan	2329
	107287
Total population	**1005254**

Table A.1: Population municipalities, Q4 2018 (*Kommunefakta*, n.d.).

A.2 Sensitivity analysis calculations

Table A.2 shows the transparent calculations and results for the sensitivity analysis conducted for this paper.



Uncertainty and sensitivity								
Plastic waste bags(pwb)	dP_{pwb}	$R0_{pwb}$	dR_{pwb}	dR	dR%	SR		
Weight per bag	5 %	508,79	534,23	2027,41	1,27 %	0,254		
	-5 %	508,79	483,35	1976,53	-1,27 %	0,254		
Bags per week	10 %	508,79	559,67	2052,85	2,54 %	0,254		
	-10 %	508,79	457,91	1951,09	-2,54 %	0,254		
Households	1 %	508,79	513,88	2007,06	0,25 %	0,254		
	-1 %	508,79	503,70	1996,88	-0,25 %	0,254		
Incorrectly sorted plastics from OHW(is	dP_{isp}	$R0_{isp}$	$R0_{OHW}$	dR_{OHW}	dR_{isp}	dR	dR%	SR
OHW delivered	4 %	380,19	44798,69	46590,64	392,53	2014,31	0,62 %	0,154
	-4 %	380,19	44798,69	43006,74	362,34	1984,12	-0,89 %	0,223
w% plastics OHW	15 %	380,19	-	-	437,22	2059,00	2,85 %	0,190
	-15 %	380,19	-	-	323,16	1944,94	-2,85 %	0,190
Plastic packaging from COW(pp)	dP_{pp}	$R0_{pp}$	$R0_{COW}$	dR_{COW}	dR_{pp}	dR	dR%	SR
COW delivered	4 %	1112,99	9678,20	10065,33	1157,51	2046,49	2,22 %	0,556
	-4 %	1112,99	9678,20	9291,07	1068,47	1957,45	-2,22 %	0,556
w% plastics COW	25 %	1112,99	-	-	1391,24	2280,22	13,90 %	0,556
	-25 %	1112,99	-	-	834,74	1723,72	-13,90 %	0,556
Bio-fertilizer(bf)	dP_{bf}	$R0_{bf}$	$R0_{bio}$	dR_{bio}	dR_{bf}	dR%	SR	
Bio-fertilizer produced	10 %	4,47	103566,20	113922,82	4,92	10,00 %	1,00	
	-10 %	4,47	103566,20	93209,58	4,03	-10,00 %	1,00	
Plastics in bio-fertilizer > 4 mm	33 %	4,47	-	-	5,97	33,33 %	1,01	
	-33 %	4,47	-	-	2,98	-33,33 %	1,01	

Table A.2: Sensitivity analysis calculations.

A.3 Guidelines for pick-analyses

Here follows a summary of the guidelines for how pick-analyses are conducted as stated by Syvertsen et al. (2015) in “Veileder-plukkanalyser” given by Avfall Norge. The guidelines are based on national assessments and experiences, international literature, manual for pick analysis by Avfall Sverige (U2013:11), and a separate report about correction factors.

The samples studied in each pick-analysis has an inhomogeneous composition that variates considerably over time and place. Further, the samples constitute a very small portion of the total share of waste the analysis represents. These factors contribute to uncertainties regarding the results and should be considered when using data from pick-analysis.

To conduct pick-analyses that are the most representative and accounts for seasonal variations like temperature and vacations, Avfall Norge recommends that pick-analyses are carried out in the periods of February - March and September – November. Waste analyzed in pick-analyses are not compressed, hence the area of pick-analyses are not exceeding voluminous limits of the waste trucks.

For OHW, it is suggested that one separates between OHW and absorbent kitchen paper. OHW is further divided into the subgroups of usable and non-usable OHW. Usable food waste is edible food that goes to waste, be it fruit and vegetables, bread and bakeries, meat and fish, dairy, leftovers and others while non-usable OHW is un-edible food that goes to waste, be it fruit stones, peels, and bones. The plant residue and garden debris is not categorized as OHW because they belong to a unique category different to usable and non-useable.

A.4 MFA results

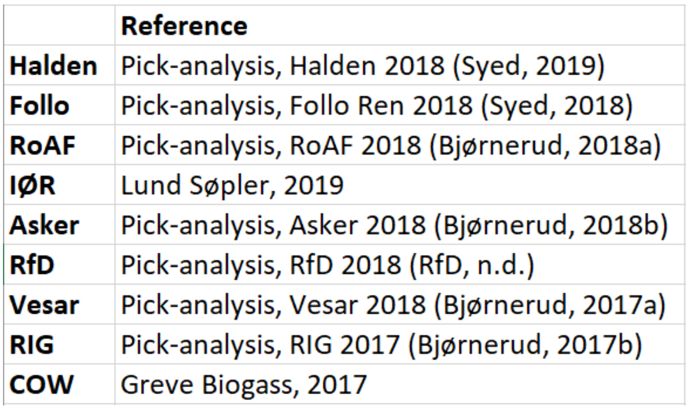
Table A.4 showing all flows and flow names with references for the MFA.

Flow and flow names with values and references									
Flow	**Flow name**	**From**	**To**	**Wet weight**	**Dry matter**	**Plastic weight**	**References wet weight**	**References dry matter**	**References plastic weight**
A_{0-1} - LAM	Liquid animal manure	0	1	64109,60	3205,48	negligible	Hegg 2019	calc. from param.	Hegg 2019
A_{0-2} - LOIW	Liquid organic industrial waste	0	2	6034,40	422,41	negligible	Hegg 2019	calc. from param.	Hegg 2019
A_{0-2} - SL	Substrate Lindum	0	2	128,20	15,38	negligible	Hegg 2019	calc. from param.	Hegg 2019
A_{0-3} - Halden	Halden kommune	0	3	1250,00	412,50	10,64	Edvardsen 2019	calc. from param.	calc. from param.
A_{0-3} - RoAF in	Romerike avfallsforedling in	0	3	-	-	-	-	-	-
A_{0-3} - Follo Ren	Follo Ren	0	3	-	-	-	-	-	-
A_{3-0} - Losses OHW to incineration	Losses organic household waste to incineration	3	0	2258,89	745,43	19,61	calc. from param.	calc. from param.	calc. from param.
A_{3-4} - RoAF out	Romerike avfallsforedling out	3	4	9630,00	3177,90	83,59	Skovly 2019	calc. from param.	calc. from param.
A_{0-4} - IØR	Indre Østfold Renovasjon	0	4	2156,00	711,48	18,35	Borgeraas 2019	calc. from param.	calc. from param.
A_{0-4} - Asker	Asker kommune	0	4	3489,31	1151,47	23,73	Hage 2019	calc. from param.	calc. from param.
A_{0-4} - RfD	Renovasjonsselskapet for Drammensregionen	0	4	10867,00	3586,11	184,74	Holen 2019	calc. from param.	calc. from param.
A_{0-4} - Vesar	Vesar	0	4	13811,86	4557,91	55,25	Nygård 2019	calc. from param.	calc. from param.
A_{0-4} - RiG	Renovasjon i Grenland	0	4	4844,52	1598,69	14,53	Høines 2019	calc. from param.	calc. from param.
A_{0-4} - COW	Commercial organic waste	0	4	9678,20	3193,81	1112,99	Hegg 2019	calc. from param.	-
A_{1-4} - LAM to pret.	Liquid animal manure to pre-treatment	1	5	64109,60	3205,48	negligible	Hegg 2019	calc. from param.	Hegg 2019
A_{2-4} - LOIW to pret.	Liquid organic industrial waste to pre-treatment	2	5	6162,60	437,79	negligible	Hegg 2019	calc. from param.	Hegg 2019
A_{4-5} - OW to pret.	Organic waste to pre-treatment (upstream)	4	5	54476,89	17977,37	380,19	mass balanced	calc. from param.	calc. from param.
A_{4-5} - OW to pret.	Organic waste to pre-treatment (registrered)	4	5	52200,80	17226,26	-	Hegg 2019	calc. from param.	-
A_{5-0} - Rejected OW to incineration	Rejected organic waste to incineration (upstream)	5	0	10895,38	4358,15	outdated data	calc. from param.	calc. from param.	outdated data
A_{5-0} - Rejected OW to incineration	Rejected organic waste to incineration (registered	5	0	10440,16	4176,06	outdated data	calc. from param.	calc. from param.	outdated data
A_{5-4} - to buffer tank	to buffer tank (upstream)	5	6	113853,71	14800,98	3,48	mass balanced	calc. from param.	calc. from param.
A_{5-4} - to buffer tank	to buffer tank (registered)	5	6	112032,84	14564,27	3,42	mass balanced	calc. from param.	calc. from param.
A_{6-7} - to sanitation	to sanitation (upstream)	6	7	113853,71	14800,98	3,48	mass balanced	calc. from param.	calc. from param.
A_{6-7} - to sanitation	to sanitation (registered)	6	7	112032,84	14564,27	3,42	mass balanced	calc. from param.	calc. from param.
A_{7-8} - to bioreactor	to bioreactor (upstream)	7	8	113853,71	14800,98	3,48	mass balanced	calc. from param.	calc. from param.
A_{7-8} - to bioreactor	to bioreactor (registered)	7	8	112032,84	14564,27	3,42	mass balanced	calc. from param.	calc. from param.
A_{8-9} - Bio gas (Nm3)	Bio gas	8	9	9258082,54	-	-	calc. from param.	-	-
A_{8-10} - Bio-fertilizer	Bio-fertilizer	8	10	103566,20	5178,31	4,47	Hegg 2019	calc. from param.	calc. from param.
A_{9-0} - Bio gas-97% to market (Nm3)	Bio gas to market 97% (Nm3)	9	0	5832592,00	-	-	Hegg 2019	-	-
A_{10-0} - Bio-fertilizer to farmers	Bio-fertilizer to farmers	10	0	103566,20	5178,31	4,47	Hegg 2019	calc. from param.	calc. from param.

Table A.4: Flow and flow names with values and references.

A.5 Pick-analysis references

Table A.5 shows the references for table 3.1: Detailed results of the pick-analyses.



	Reference
Halden	Pick-analysis, Halden 2018 (Syed, 2019)
Follo	Pick-analysis, Follo Ren 2018 (Syed, 2018)
RoAF	Pick-analysis, RoAF 2018 (Bjørnerud, 2018a)
IØR	Lund Søpler, 2019
Asker	Pick-analysis, Asker 2018 (Bjørnerud, 2018b)
RfD	Pick-analysis, RfD 2018 (RfD, n.d.)
Vesar	Pick-analysis, Vesar 2018 (Bjørnerud, 2017a)
RIG	Pick-analysis, RIG 2017 (Bjørnerud, 2017b)
COW	Greve Biogass, 2017

Table A.5: References for pick-analyses.