Universität für Bodenkultur Wien
University of Natural Resources and Life Sciences, Vienna

Department of Sustainable Agriculture Systems

Institute of Agricultural Engineering

Life Cycle Assessment of biogas and nano-cellulose production from elephant manure

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submitted by

Theresa Krexner

supervised by

Univ. Prof. Dipl.-Ing. Dr. Andreas Gronauer

Dipl.-Ing. Dr. Iris Kral

Ass. Prof. Dipl.-Ing. Dr. Alexander Bauer

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Affidavit

I give my solemn word that I have compiled this work solely and without external help, have not utilized any sources outside those permitted and that the sources used have been given verbatim or quoted textually in the places indicated.

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Abstract

Nano fibrillated cellulose (NFC) is a unique new material with a wide range of potential applications; still research of environmental impacts in the industrial scale is scarce. The step from raw material (pulp is commonly used) to NFC requires a lot of energy. In this thesis a new approach to produce NFC from the fermentation residue of anaerobically digested elephant manure (manure scenario; MS) is compared to the production from Kraft pulp from hardwood chips (wood chips scenario; WCS). A proxy approach is used to upscale MS from a laboratory to an industrial scale (except for the pulp to NFC step) to ensure comparability. Since the MS is a multi-output process (biogas and NFC) a biogas plant with maize silage and pig slurry as substrate is added to WCS for comparison of equal benefits. The impact categories (global warming potential (GWP), fossil resource scarcity, freshwater eutrophication (FEP), human toxicity, terrestrial acidification (TAP) and terrestrial ecotoxicity potential (TEP)) are analysed referring to the functional unit of 1 kg NFC with Recipe2016 (H) method and the Ecoinvent database v3.6. Results show that MS has lower impacts in all assessed categories. GWP is 4,41 kg CO_2 eq./kg NFC in MS; 9,74 kg CO_2 eq./kg NFC in WCS. The pulp to NFC step is identified as hotspot in both scenarios causing 35,11 % (MS) and 21,79 % (WCS) in TEP and 81,49 % (MS) and 93,38 % (WCS) in FEP, which is in line with other studies. Biogas production has the lowest impact in FEP of MS and WCS (13,22 %; 5,14 %, respectively), and the highest impacts in TAP (74,46 %, MS) and TEP (25,66 %; WCS). Resultant, maize silage production is found as another hotspot. Pulp production has the highest impact in TEP of MS and WCS (39,24 %; 19 %, respectively) and lowest impacts in FEP (5,29 %; MS) and FRS (5,84 %; WCS). The LCA shows that the production of NFC from elephant manure is a sustainable alternative to the production from hardwood Kraft pulp.

Kurzfassung

Nano-fibrillierte Cellulose (NFC) ist ein neuartiges Material, welches viele mögliche Anwendungsgebiete hat. Dennoch gibt es nur wenige Studien über die Umweltauswirkung der Produktion. V.a. der Schritt vom Ausgangsmaterial (meistverwendet ist Pulp) zu NFC benötigt viel Energie. In dieser Arbeit wird der neue Ansatz NFC aus dem Gärrest fermentierten Elefantendungs („manure scenario"; MS) herzustellen und die Erzeugung aus Kraft Pulp („wood chips scenario"; WCS) bzgl. ihrer Umweltauswirkungen mithilfe einer Ökobilanz verglichen. Mit einem Proxy-Ansatz wird der MS Laborprozess in den Industriemaßstab hochskaliert (ausgenommen der Verarbeitungsschritt Pulp zu NFC), um Vergleichbarkeit mit WCS herzustellen. Im MS werden sowohl Biogas als auch NFC produziert, daher wird im WCS eine Biogasanlage hinzugefügt. Die Wirkungskategorien Treibhausgaspotenzial (GWP), fossile Ressourcenknappheit, aquatisches Eutrophierungspotenzial (FEP), Humanökotoxizität, terrestrisches Versauerungspotenzial (TAP) und terrestrische Ökotoxizität (TEP) wurden, jeweils auf die funktionelle Einheit 1 kg NFC bezogen, ausgewertet. Die Auswertung zeigt, dass MS in allen Kategorien geringere Umweltauswirkungen hat. Das GWP von MS ist 4,41 kg CO_2 Äq./kg NFC, das von WCS 9,74 kg CO_2 Äq./kg NFC. Besonders sticht der letzte energieintensive Produktionsschritt heraus: MS: zwischen 35,11 % (TEP) und 81,49 % (FEP); WCS: zwischen 21,79 % (TAP) und 93,38 % (FEP). Die Biogasproduktion hat die geringste Umweltauswirkung in beiden Szenarien in FEP (13,22 % MS; 5,14 % WCS), die größte in TAP (74,46 %, MS) und TEP (25,66 %; WCS). Die Substratproduktion im WCS wurde als weiterer Hotspot identifiziert, besonders im TAP. Die Pulpproduktion hat die größte Umweltauswirkung in beiden Szenarien in TEP (39,24 % MS; 19 % WCS), die geringsten in FEP (5,29 %; MS) und FRS (5,84 %; WCS). Diese LCA zeigt, dass NFC aus Elefantendung eine nachhaltige Alternative zu Kraft Pulp ist.

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General abbreviations

AD	anaerobic digestion
ADF	acid detergent fibre
ADL	acid detergent lignin
BNC	bacterial nano-cellulose
CHP	combined heat and power
CEHO	chloroacetic acid etherification and homogenization
CESO	chloroacetic acid etherification and sonication
CEPI	Confederation of European Paper Industries
DM	dry matter
ECF	elemental chlorine free
FM	fresh matter
FU	functional unit
GHG	greenhouse gas
GSD	geometric standard deviation
IPCC	Intergovernmental Panel on Climate Change
IRR	integrated resource recovery
LCA	life cycle assessment
LCCA	life cycle cost assessment
LCI	life cycle inventory
LCIA	life cycle impact assessment
LCSA	life cycle sustainability assessment

MFC	micro fibrillated cellulose
NCC	nanocrystalline cellulose
NDF	neutral detergent fibre
NFC	nano fibrillated cellulose
oDM	organic dry matter
SC	super-calendered
SLCA	social life cycle assessment
TCF	totally chlorine free
TMP	thermo-mechanical pulp
TOHO	2,2,6,6-Tetramethylpiperidinyloxyl-oxidation and homogenization
TOSO	2,2,6,6-Tetramethylpiperidinyloxyl-oxidation and sonication
PP	polypropylene

Chemical elements and compounds

AOX	adsorbable organic halides
$CaCO_3$	calcium carbonate
CaO	calcium hydroxide
CH_4	methane
ClO_2	chlorine dioxide
CO_2	carbon dioxide
kg CO_2 eq.	a kilogramme carbon dioxide to air equivalent
kg oil eq.	a kilogramme of oil equivalent
kg PO_4^{3-} eq.	a kilogramme of phosphate equivalent
kg SO_2 eq.	a kilogramme of sulphur dioxide equivalent

kg 1,4-DCB	a kilogramme of 1,4-dichlorobenzene
COD	chemical oxygen demand
H_2O_2	hydrogen peroxide
$MgSO_4$	magnesium sulfate
N_2O	nitrous oxide
Na_2CO_3	sodium carbonate
NaOCl	sodium hypochlorite
NaOH	sodium hydroxide
Na_2S	sodium sulphide
NO_X	nitrogen oxide
O_2	oxygen
SO_2	sulphur dioxide

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1. Introduction

In two millennials of papermaking the fundamental process has hardly changed. Fibres are suspended in water, then the suspension is dewatered, finally the fibres form a coherent fleece (UPM-Kymmene Corporation, 2005). From the invention of paper in 105 A.D., which is credited to Ts'ai Lun of China (Biermann, 1996) to this day a big pulp and paper industry has come up which was not only the third largest energy intensive industry in 2012 in the OECD industrial sector (U.S. Energy Information Administration, 2016), but also is one of the heaviest users of fresh water and therefore counts as one of the biggest polluters worldwide (Environmental Paper Network, 2018).

Alone in 2017 the world total pulp production was 184,4 million tonnes with the largest share of 34,9 % of North America, 22 % of Asia and 20,6 % of CEPI (Confederation of European Paper Industries; European non-profit making organisation representing the forest fibre and paper industry) members. In comparison, in the same year the paper and board production was 419,7 million tonnes with the largest share of 47 % of Asia, followed by 22 % of CEPI members and 19,6 % of North America (CEPI, 2019).

The Environmental Paper Network (2018) stated that the paper consumption is globally steadily increasing, particularly in Asia due to higher living standards. One factor for the increase in paper use can be explained by the application as packaging material. Further, substantial climate change impacts can be attributed to the pulp and paper industry through the whole product life cycle, starting with harvesting the raw material, through the energy and water intensive production to the end of life of their products.

CEPI (2019) states that the trend in paper and board production within the CEPI members (Austria, Belgium, Czech Republic, Finland, France, Germany, Hungary, Italy, The Netherlands, Norway, Poland, Portugal, Romania, Slovakia, Slovenia, Spain, Sweden, and United Kingdom) is increasing in a linear fashion leading to a total production of board and paper in 2018 of 92,2 million tonnes in more than 900 pulp and paper mills across Europe. Germany is the main producer with a share of 24,6 %, while Austria plays a subordinate role with a share of 5,5 %.

Although the need of reducing substantial climate change impacts are required (Environmental Paper Network, 2018), the total amount of paper and board is produced by 41,2 % from pulp, which is made 99,27 % from wood (72,4 % softwood) (CEPI, 2019). Thereby, it must be taken into consideration, that the raw material wood should be used as sparingly as possible, because in theory it can also replace fossil fuels elsewhere and the pressure to use the resource wood increases overall (Umweltbundesamt, 2014). The most used wood species in the CEPI member countries are pine and spruce with 84,3 % of the material coming from the CEPI area (CEPI, 2019).

Further the pulp and paper industry is very water intensive. The total amount of water intake in 2017 of CEPI member countries was 3,457 million m^3 (CEPI, 2019). In the production of paper water is required for the general production, for auxiliary and for cleaning purposes, whereby it is used several times within the production process. Nowadays, carefully cleaned process water goes through the production process up to ten times. In modern pulp mills 40 cubic meters of waste water per ton of pulp arise. Another problem occurs, because waste water from pulp and paper mills is usually very heavily contaminated with organic carbon compounds. Some of these are difficult to degrade and can only be partially degraded in the biological sewage treatment plants (Umweltbundesamt, 2014).

In addition to the waste water the pulp and paper industry emits emissions which consists of a mix of carbon dioxide (CO_2), nitrogen oxide (NO_X), sulphur dioxide (SO_2) as air emissions and chemical oxygen demand (COD) and adsorbable organic halides (AOX) as water emissions. In 2017 the absolute CO_2 emissions from CEPI member countries amounted to 32,22 Mt which is 0,30 kg CO_2 / kg of product (CEPI, 2019).

The Environmental Paper Network came up with seven goals to minimize climate change impacts from the pulp and paper industry, including a goal to source fibre responsibly. To not risk further deforestation worldwide, alternatives for wood fibres should always be considered (Environmental Paper Network, 2018).

Alternatives for wood are hemp, flax, bamboo, kenaf, and agricultural residues such as wheat straw and bagasse (Favero, Thomas and Luettgen, 2019). For instance, in China agricultural waste fibres accounted for more than 50 % in 2004 (Environmental Paper Network, 2018). Another upcoming trend is the waste-to-resource path which uses a waste stream as valuable resource. Within this approach manure as a by-product from farms can be used as resource for pulp and papermaking due to its relatively high cellulose content up to 40 % depending on the animal (Meissner et al., 1990). Nowadays, manure is widely used as substrate for biogas plants, therefore providing energy and a fermentation residue containing valuable nutrients which can be used as a fertilizer in agriculture (Holm-Nielsen, Al Seadi and Oleskowicz-Popiel, 2009). A novel sustainable approach is to first anaerobically digest manure and produce biogas and further using the cellulose-containing fermentation residue as pulp resource.

2. State of knowledge

2.1. Life cycle assessment (LCA) of biogas systems

There are lots of studies about the topic biogas with its various substrates. The majority of studies focuses on the environmental impacts of different raw materials as input substrates or on the comparison to fossil-based energy systems while just a few use the LCA method to assess integrated systems and their benefits. Integrated biogas systems are circulatory systems that make optimal use of the input material to produce energy and heat in a process where all by-products are used as input material for another process (IEA Bioenergy, 2018). This chapter focusses on the comparison between LCA of biogas from manure compared to energy crops and on LCAs of integrated systems which use manure as input material to produce biogas such as the model in the present thesis.

2.1.1. LCA of biogas from manure and energy crops

Fuchsz and Kohlheb (2015) analysed in their study the environmental effects of farm-scaled anaerobic digestion (AD) plants using energy crops and manure as raw material using life cycle assessment. Their functional unit was the exported electricity into the grid in kWh that was produced in a cogeneration unit from burning biogas. For the use of manure as raw material just the direct emissions at the AD plant were considered, because environmental effects of animal breeding and the necessary crop cultivation are mainly attributed to the main products meat and/or milk. For the use of energy crops as raw material the full up-flow streams are considered. One main goal was to determine the impact of the building of the biogas plants. The examined impact categories were the global warming potential (GWP), the eutrophication potential and the acidification potential. According to Fuchsz and Kohlheb (2015) the higher the share of processing lower-energy-density substrate (e.g. manure or slurry) the higher the numbers for GWP, eutrophication potential and plants own energy consumption. While the biogas plant using only energy-crops had a GWP of 1661 kg CO_2 eq./kWh, the biogas plant with only manure as input material the GWP was 4.015 kg CO_2 eq./kWh. The eutrophication potential of the biogas plant with manure as input material was more than two times higher (5,65 kg PO_4 eq./kWh in contrast to 2,58 kg PO_4 eq./kWh). On the other hand, the acidification potential of the only manure processing biogas plant was almost half than the potential of an only energy crops based one (12,98 kg SO_2 eq./kWh in contrast to 20,49 kg SO_2 eq./kWh) (Fuchsz and Kohlheb, 2015).

Boulamanti et al. (2013) evaluated the impact of different factors on the greenhouse gases (GHG) emissions of a biogas plant with a combined heat and power (CHP) engine by using an LCA approach. Different feedstocks, particularly maize silage and manure in single and in co-digestion, the management of the fermentation residue and the emissions from the end use of the biogas and the digestate were considered. As functional unit (FU) 1 MJ of electricity from the CHP was defined and the cultivation of the maize is considered. The digestion of pure maize silage or manure, as well as co-digestion of these two inputs were compared to the production of 1 MJ electricity from the European energy mix (reference scenario). The GWP of the biogas plants with various feedstocks were all lower than the reference systems (~150 kg CO_2 eq./MJ) with savings from 3 % to 330 %. By assuming that emissions from undigested manure are avoided the highest savings were achieved in the manure scenario with a closed storage. By not considering the avoided emissions of undigested manure the manure pathway with closed storage had a GWP of 91,52 kg CO_2 eq./MJ and the pathway with an open storage a GWP of 268,92 kg CO_2 eq./MJ. The maize pathway with an open storage showed similar numbers than the reference system due to the intensive cultivation of maize. The results showed that the acidification potential is the highest in the manure scenario with an open storage (~2,5 kg SO_2 eq./MJ) especially due to ammonia emissions. As Fuchsz and Kohlhleb (2015) also Boulamanti et al. (2013) found the acidification potential to be lower when digesting manure with a closed storage than with maize silage as input material. The impact with the closed storage was decreased to ~1,0 kg SO_2 eq./MJ. The biogas plants with co-digestion and an open and closed storage had an impact of ~1,5 – 1,75 kg SO_2 eq./MJ, while the maize silage pathways had an impact of ~1,75 kg SO_2 eq./MJ, the reference scenario had an impact of ~0,5 kg SO_2 eq./MJ. The highest contributors were the open storage in the manure pathway, in the other pathways the CHP and the maize silage production. The impact of the reference pathways played a subordinate role, while the other pathways showed high impacts, especially the maize and co-digestion pathways (~13 P eq./MJ and ~11 P eq./MJ, respectively). The biogas plants with manure as substrate had an impact of ~3 P eq./MJ. Cultivation was found to be the main contributor to the freshwater eutrophication potential, therefore the high numbers in the maize and co-digestion pathways are explained. The main contributor to the terrestrial ecotoxicity is again the cultivation. 80 % of the impact of the cultivation is due do the pollution of agricultural soils with heavy metals. The results for the maize pathways were between 35 and 37,5 kg 1,4-DCB/MJ, for the co-digestion pathways ~30 kg 1,4-DCB/MJ and for the manure scenario ~0,5 kg 1,4-DCB/MJ. The reference scenario had an impact of ~0,1 kg 1,4-DCB/MJ. All in all, Boulamanti et al. (2013) stated that two factors have the highest impact on the sustainability of a biogas plant: the input material and the management of the digestate. Further, they showed that closed storage helps to avoid uncontrolled emissions of diverse emissions like methane, nitrous oxide or ammonia.

Kral et al. (2016) evaluated the difference between the input materials maize silage and maize stover, both co-digested with pig slurry in a typical large Austrian biogas facility with a CHP unit using a life cycle approach. Due to the poorly digestibility of maize stover, steam explosion as a pre-treatment is used and the environmental burdens of it compared to the typical used energy crop input maize silage are analysed. The chosen functional unit is 1 kWh electrical energy from the CHP unit, for the analysed scenarios the biogas facilities (including construction materials and their transportation, methane leaks from the fermenter, the pre-treatment for the maize stover scenario), the CHP unit and the production and transportation of the maize silage and maize stover are taken into account. The findings showed that the maize stover scenario results in lower environmental impacts in all analysed impact categories. The GWP of the maize silage scenario is slightly higher than of the maize stover scenario (0,287 kg CO_2 eq./kWh in contrast to 0,239 kg CO_2 eq./kWh). The methane slip of the CHP module contributes mainly to the climate change (46 % for the maize silage scenario and 56 % for the maize stover scenario). For the maize silage scenario the production of the input material has the second highest share (24 %) while for the maize stover scenario it is the electricity for the biogas plant operations (18 %). Overall, the maize stover scenario leads to lower climate change impact compared to maize silage as input, namely 83 % of the maize silage scenario. A big difference in the numbers can be explained with the contribution of the input material: as maize stover is a secondary agricultural substrate it leads to a drastically lower climate change impact (9 % of the total GWP is contributed by the maize stover production which is 0,021 kg CO_2 eq./kWh). For the terrestrial acidification mainly the CHP unit and the substrate production contributed to the category, the highest share is coming from ammonia from the fermentation residue application as fertilizer (97 % and 95 % for the maize silage and the maize stover scenario, respectively). In total the scenarios had a terrestrial acidification potential of 0,018 kg SO_2 eq./kWh (maize silage) and 0,008 kg SO_2 eq./kWh (maize stover). The main contributor to the human toxicity potential was found to be the substrate production with zinc emissions from the fermentation residue having the highest impact. In total the impact was 0,029 kg 1,4-DCB/kWh (maize silage) and 0,012 kg 1,4-DCB/kWh (maize stover) (Kral et al., 2016).

2.1.2. LCA of biogas from manure in a circulatory system

Zhang, Bi and Clift (2013) evaluated the environmental benefits of an integrated dairy farm-greenhouse system in British Columbia. Manure accounts for 82 % of the total organic waste in that area and greenhouse cultivation is another big agricultural system by consuming 36 % of the total natural gas demand of the agricultural sector. This study fully assessed the waste-to-resource path and compared it to a conventional system. Manure is anaerobically digested, the emerging biogas is used for the greenhouse and the livestock farm heating (instead of natural gas) and the digestate is separated into a liquid phase that is used as fertilizer and a solid phase used as cow bedding material and growing material for the greenhouse instead of sawdust. The selected impact categories were non-renewable energy consumption, climate change impact, aquatic acidification, aquatic eutrophication, respiratory effects and human toxicity. Since the manure accounts for such a high percentage of the organic waste in the area “disposal of 1.100 tonnes of organic waste” was selected to be the functional unit. Six different cases were analysed, whereby in three cases 100 % manure was used (exclusively dairy manure or a mix of it with 20 % either swine or poultry manure) and in the other three cases mixtures of dairy manure with plant (20 %), food (20 %) or fat, oil and grease (10 %) waste. For every case the baseline scenario using natural gas and two different approaches of an integrated system were examined. The non-renewable energy consumption was significantly reduced due to the replacement of natural gas by biogas (from 1.400-2.200 GJ to around 400 GJ or less). Also, the use of the solid phase as cow bedding material and greenhouse growing medium accounts positively to this impact factor. The main contributor to GWP was found to be the natural gas combustion in the baseline scenario, for the integrated systems the main contributor was the composting of surplus digestate. For the baseline scenario in the different cases the GWP was 140-250 t CO_2 eq./disposal of 1.100 tonnes of organic waste and for the integrated systems ~40 t CO_2 eq./disposal of 1.100 tonnes of organic waste. Overall, climate change impacts and aquatic acidification reductions (65-90 %) were found in the integrated system mainly for the reason of no long-term manure storage. In total all impact factors were found to be reduced within the integrated system in comparison to the baseline scenario using natural gas leading to the conclusion that integrative systems with a waste-to-resource approach can provide environmental benefits compared(Zhang, Bi and Clift, 2013).

Another study of an integrated system was conducted in Vietnam by Nhu et al. (2015) using the concept of integrated resource recovery (IRR) in which “waste” is seen as a potential resource. In Asia integrated agricultural-aquaculture systems are common waste management strategies. Due to the rapid growth of Vietnamese livestock production a new way of manure management had to be found. This led to the new approach of a “Vuon, Ao, Chuong – Garden, Aquaculture, Animal husbandry” combined with anaerobic digestion. Livestock manure, in this study mainly pig manure, is used to produce biogas for the use in households. The liquid digestate fraction can be used as fertilizer in aquaculture while the sediment from the pond can be used as fertilizer for crops. The study’s aim was to present the benefits of an integrated system compared to a monoculture one. The functional unit was “sum of products”, defined as the sum of one kilogram of pig products (culled sows and finishing pigs), fish products (culled brood-stock, fingerlings and market-sized fish), methane and pond sediment. The study showed that the integrated systems were mainly based on land and water resources (54-62 % and 28-42 %, respectively). The main share of the land is originating from the agricultural land demand. Further it was shown that with the integrated system a reduced resource demand depending on less feed use in aquaculture and avoided resource burdens (avoided burden of around 10 MJ in the integrated system in contrast to avoided burden of 0,4 MJ in the monoculture system) by substitution of biogas for natural gas in households and pond sediment for plant fertilizer could be achieved (Nhu et al., 2015).

2.2. Overview Kraft pulping process

The Kraft (sulphate) pulping process is the most common applied method for producing pulp. 80 % of the worlds pulp production is produced by it due to many benefits like efficient chemical recovery system, applicability to all wood species and most likely because of the superior strength properties, while the sulphite process is nowadays rarely used and accounts for only 10 % (Suhr et al., 2015). Therefore, this chapter will exclusively focus on the sulphate process which is illustrated in Figure 1.

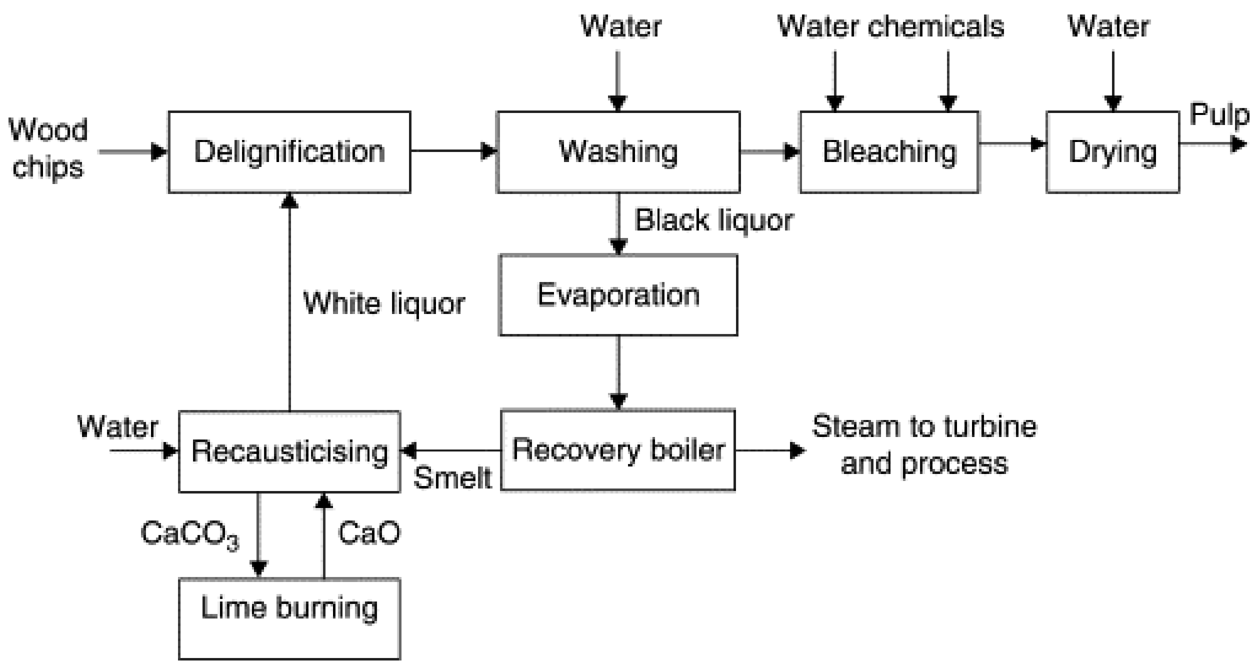

Figure 1: Overview of the Kraft pulping process (Bonhivers and Stuart, 2013)

Pulp mills usually get their wood as raw material delivered as uniform-sized chips thereby the more uniform the chips the lower the raw material consumption. The three main components of wood are cellulose, lignin and hemicellulose, but only the cellulose is needed for producing pulp. Therefore, with the help of cooking chemicals (white liquor) containing sodium hydroxide (NaOH) and sodium sulphide (Na_2S) the lignin and partially the hemicellulose are dissolved in a digester. After the delignification step the pulp contains fibres and the spent cooking liquor (black liquor). Through a washing step the black liquor and some dissolved organic substances are separated from the pulp. Further the pulp is screened with pressure screens to avoid fibre bundles. After cooking, the oxygen delignification is done in one or two steps by adding magnesium salt ($MgSO_4$) to preserve the strength of the pulp and oxidised white liquor. Another washing step in one or two phases recovers organic material. As cooking and oxygen delignification cannot remove all the lignin and therefore result in a rather low brightness, a bleaching step is needed to enhance the brightness. Bleaching can be distinguished in elemental chlorine free (ECF) and totally chlorine free (TCF) types. This step is usually carried out in four to five steps but nowadays three-steps mills are getting more common. The most common chemicals applied are chlorine dioxide (ClO_2), oxygen (O_2), hydrogen peroxide (H_2O_2) and sodium hydroxide. Finally, the bleached pulp is again screened. In an integrated pulp and paper mill, meaning that the pulp and paper production take place in one mill, the pulp is further used for paper production. In a non-integrated pulp mill, meaning the pulp and paper production take place in different places, the pulp is dried and then ready for transportation. The drying step consists of the dewatering stage, steaming with a multistage dryer and cutting in sheets and bale forming for transportation (Suhr et al., 2015).

When the black liquor is separated from the pulp after the washing step it is first processed by several evaporators and then sent to the recovery boiler. There the black liquor is combusted with air producing high-pressure steam that can be used on the production site to produce power and steam with a turbine. Through the combustion smelt is built up in the recovery boiler, mainly consisting of sodium carbonate (Na_2CO_3) and sodium sulphide. In the final recausticising step calcium hydroxide (CaO) is added to the sodium carbonate to recover sodium hydroxide and producing calcium carbonate ($CaCO_3$) which is regenerated by heating in the lime kiln. The recovered sodium hydroxide and sodium sulphide are again used for the delignification step (Bonhivers and Stuart, 2013).

2.3. LCA of the pulp and paper industry

Lopes et al. (2003) focused in their study about the Portuguese printing and paper production on the comparison between the use of two different fuels, heavy fuel oil and natural gas. A further study assessed again the environmental impacts of the production of printing and writing paper in Portugal but focused on the comparison between the consumption of the paper at the German and Portuguese markets (Dias, Arroja and Capela, 2007). For both studies the used pulp was made from Eucalyptus globulus, the functional unit was set to “1 t of white printing and writing paper, with a standard weight of 80 g/m²”. The assessed impact categories were GWP over 100 years, acidification potential, eutrophication potential, non-renewable resource depletion and photochemical oxidant formation. The examined life cycle included the production of E. globulus, the pulp production from E. globulus and pine as well as the final disposal (recycling, landfilling and composting) (Dias, Arroja and Capela, 2007; Lopes et al., 2003). While Lopes et al. (2003) assumed the whole life cycle to be in Portugal, Dias et al. (2007) included a distribution of the product to Germany to focus on the difference of the German and Portuguese market including the final disposal in the countries associated. Within the results the pulp production sub-process was found to be the main consumer of renewable energy (80 % or ~1.200 MJ), due to the fact, that bark and black liquor are used as energy fuels on site. This sub-process also played a major role for the NO_x emissions due to transportation of E. globulus, COD emissions due to E. globulus pulp production and AOX emissions due to the use of chlorine dioxide as bleaching agent. On the other hand, the paper production sub-process was found to be the main consumer of non-renewable energy consumption (for the scenarios of heavy fuel oil ~40 % and ~60 % for the natural gas). The results of the air emissions category showed that by replacing heavy fuel oil with natural gas CO_2 emissions can be reduced by around 50 % since the main contributor is the on-site energy production. Similar, the NO_x emissions can be reduced by around 40 % by using natural gas since the most important distributor are the transportation of eucalyptus by truck and the black liquor combustion. The disposal of wastepaper is the main contributor in both scenarios to the GWP (~58 % in the heavy fuel oil scenario and ~63 % in the natural gas scenario). In total the GWP of the natural gas scenario is around 20 % lower than in the heavy fuel oil scenario (~3.000 kg CO_2 eq./FU in contrast to ~3.600 kg CO_2 eq./FU) since especially CO_2 emissions could be decreased. By replacing heavy fuel oil to natural gas, the total acidification potential can be reduced by around 75 % (from ~14 kg SO_2 eq./FU to 3 kg SO_2 eq./FU) since the impact of the paper production is decreased to around zero emissions for the natural gas scenario and the assumption that emissions can be avoided by surplus electricity. The pulp production sub-process is the main contributor to eutrophication potential, mainly through the production of pulp from E. globulus, and was found to be the main contributor to water emissions due to COD and AOX emissions. With the replacement of heavy fuel oil by natural gas the total eutrophication potential was reduced by 20 % (2 kg PO_4^{3-} eq./FU to 1,6 kg PO_4^{3-} eq./FU) (Dias, Arroja and Capela, 2007; Lopes et al., 2003).

Lopes et al. (2003) stated that the use of natural gas in the eucalyptus pulp and paper production instead of heavy fuel oil lead to a decrease in the total emissions of CO_2, SO_2 and NO_x which leads to smaller environmental burdens within GWP, acidification and eutrophication potential. Further, the comparison between consumption at the German or Portuguese market showed that consuming the paper in Portugal leads to lower environmental impacts in the distribution due to shorter transportation ways, but higher impacts in the final disposal compared to Germany (Dias, Arroja and Capela, 2007).

A study from Ghose and Chinga-Carrasco (2013) evaluated the production of Kraft and thermo-mechanical pulp (TMP) and two different types of printing paper (super-calendered (SC) paper and newsprint) in Norway in the period from 2008 to 2011. A “cradle-to-gate” approach was chosen, therefore the forestry, the use and disposal phase were not considered. 13 impact categories were analysed, including GWP, ozone depletion potential (ODP), human toxicity potential (HTP), photochemical oxidant formation (POF), particulate matter formation, ionising radiation, terrestrial acidification potential (TAP), freshwater eutrophication potential (FEP), marine eutrophication potential, terrestrial ecotoxicity potential (TEP), freshwater ecotoxicity, marine ecotoxicity and the cumulative energy demand (CED). The GWP of the newsprint production showed a significant difference between the usage of the

Norwegian energy mix and a mix of imports from European and Scandinavian and domestic plants (211 (271) kg CO_2 eq./FU in contrast to 512 (625) kg CO_2 eq./FU, respectively for the years 2011 and 2008). Similar results were found in the SC paper production (363 (313) kg CO_2 eq./FU in contrast to 626 (610) kg CO_2 eq./FU, respectively for the years 2011 and 2008). This difference is explained since energy imports include nuclear energy with a higher impact on climate change while the Norwegian energy mix consists only of hydro energy. One of the main contributors to the TAP, total ecotoxicity potential (terrestrial, freshwater and marine), freshwater and marine eutrophication is the used chemicals in the newsprint production (15-20 % in 2011 and around 30 % in 2008). In total, the impact of SC paper production showed a higher environmental impact in all examined impact categories (5-10 %, except in the marine eutrophication potential where it has a share of around 15 %). Another high impact is contributing from outgoing and incoming transportation for the SC paper production with a share of around 20-25 % in the examined impact categories since the road transportation and therefore the combustion of fuel has increased. Another hotspot in the human toxicity potential in the SC paper production is the treatment of residual ash which has a share of 22 %. Overall, the results showed that the TMP production lead to the highest impact in all categories for both paper types (30-70 % for newsprint and 30-60 % for SC paper). One hotspot was the used energy mix (Norwegian only or European mix) which made a huge difference (20-50 % for newsprint and 20-30 % for SC paper) due to the fact, that the energy from Norway comes exclusively from hydropower. Overall, in the production process of SC paper and newsprint the pulp production was the sub-process with the highest environmental impacts most likely due to the energy intensiveness (Ghose and Chinga-Carrasco, 2013).

A LCA study that assessed the offset paper production in Brazil including a forest production subsystem to the industrial one was conducted by Silva et al. (2015). Offset paper is usually further used as printing or writing paper. The LCA consists of two production subsystems: the forest production with all activities of forestry (seedling production, soil preparation, seedling planting, forest maintenance and wood harvesting) and the supply of eucalyptus wood to the pulp and paper plant and the industrial production including pulp extraction, bleaching, chemical recovery and the offset paper production. Silva et al. (2015) stated that the industrial production system consumes 91 % of the total energy demand (8.660 MJ in total with 65 % coming from renewable sources) with the bleaching and extraction (40 %) and offset paper manufacturing processes (~50 %) consuming the largest share. Also, the most environmental impacts could be contributed to the industrial production system (~15 % to the acidification potential and GWP, 50 % to nutrient enrichment, ~1 % to ozone depletion, ~37 % to photochemical oxidation, ~10 % to human carcinogenic toxicity and around zero to the human non-carcinogenic toxicity). Only in the ecotoxicity impact category the forest production subsystem contributed more impact than the industrial subsystem (~60 %) due to the use of glyphosate herbicides. The total GWP was 1.050 kg CO_2 eq./t of offset paper with the main share coming from the offset paper manufacturing (52 %) mainly due to CO_2 emissions from electricity production. Another main contributor is the pulp extraction and bleaching process (41 %) again due to CO_2 emissions coming from non-renewable energy sources. The total acidification potential was 10,6 kg SO_2 eq./t of offset paper with the highest share coming from the chemical recovery process (62 %) followed by the extraction and bleaching process (24 %). The results showed an impact of 34,2 CTUeco in the ecotoxicity impact category mainly due to the chemical recovery (49 %) and paper offset manufacturing (46 %). The human carcinogenic toxicity potential was $9*10^{-8}$ CTUh and $7,44*10^{-6}$ CTUh for the human non-carcinogenic toxicity potential. For both impact categories the chemical recovery process (55 % and 54 %, respectively) and the paper manufacturing process (41 % respectively) were the main contributor. Hence, Silva et al. (2015) stated that most hotspots in the offset paper production in Brazil can be contributed to the pulp extraction and bleaching process and are usually linked to the production of electricity or thermal energy from biomass and diesel combustion.

A study from Corcelli et al. (2018) assessed the whole life cycle (starting with foresting, pulp and paper making process, final distribution and the end-of-life process) of office and magazine paper from spruce and pine wood in Finland. Further the wastewater and solid waste treatment plants were also integrated to the assessed system; the energy production takes place in situ and consists of combustion of biomass waste, black liquor and sludge from the wastewater treatment plants. In order to assess the benefits of resource recovery and the energy and heat production at the pulp and paper plant a system expansion was done. The functional unit was defined as 1 t of produced paper. The results showed that the production of pulp and paper, but mainly the pulp production, affect all assessed impact categories with a joint share of up to 88 % (GWP, ODP, TAP, FEP, HTP, POF, TEP, metal depletion potential (MDP) and fossil depletion potential (FDP)). Further, the impact of the forestry subsystem showed no impact higher than 10 % in any impact category (Corcelli et al., 2018). The total GWP was -11,1 kg CO_2 eq./t paper which indicates that producing energy in situ (-1.360 kg CO_2 eq./t paper) leads to an environmental advantage. Nevertheless, the GWP of the forestry (88 kg CO_2 eq./t paper), the pulp production (982 kg CO_2 eq./t paper) and the paper production phase (832 kg CO_2 eq./t paper) must be kept in mind. Similar, the total impacts of FEP (-0,284 kg P eq./t paper), HTP (-176 kg 1,4-DCB eq./t paper) and TEP (-0,0723 kg 1,4-DCB eq./t paper) are negative. For these three impact categories the main benefit is contributed again by the in-situ energy production while the main load is coming from the pulp production phase (FEP: 0,233 kg P eq./t paper; HTP: 213 kg 1,4-DCB eq./t paper; TEP: 0,0965 kg 1,4-DCB eq./t paper). In the other impact categories, the impacts of the forestry, pulp and paper production are higher than the advantages leading to total positive values of impact. Corcelli et al. (2018) stated that the processes digesting, chemical recovery and bleaching affect GWP, ODP, TEP and FDP with around 90 % and TAP and HTP with around 80 %. This is generally due to the high energy requirements of these processes. When producing energy in situ compared a reduction in all impact categories could be found, the highest impact reduction with 70 % on GWP and FDP. Overall, the results showed again, that the industrial production stage, especially the digesting, chemical recovery and bleaching processes, is the main contributor of environmental impacts in the production chain of paper, generally due to the high electricity and heat requirements (Corcelli et al., 2018).

A study that assessed a biorefinery in Sweden in which the main product is dissolving softwood pulp with the co-products ethanol and lignosulfonates was conducted by González-García et al. (2011). What makes the biorefinery particularly interesting is the closed-loop bleaching cycle with no discharge at all. The functional unit was set to 1 t of air-dried dissolving cellulose from a mix of spruce (80 %) and pine wood (20 %) with a moisture content of 10 %. The assessed system was split in two subsystems: the forestry subsystem including silviculture operations, logging operations and the transport to the biorefinery gate and the biorefinery subsystem including all activities of the production of pulp and the other co-products. The results showed a small impact of the forestry subsystem (0,065-12,9 %, except ozone layer depletion with 34,6 %) compared to the biorefinery process chain. The high impact in ozone layer depletion was explained with the use of fossil fuels, especially in the transport of pulpwood. The main contributor to the GWP (total for biorefinery system: 393,42 kg CO_2 eq./t cellulose) was found to be the production of chemicals (especially sodium hydroxide and hydrogen peroxide) with a share of 51 % followed by the co-generation process with a share of 17 %. Similar results were found in the HTP (total for biorefinery system: 62,71 kg 1,4-DCB/t cellulose) where the main contributor was also the production of chemicals with the main share (31 %) coming again from sodium hydroxide and hydrogen peroxide. Other high contributors were the co-generation unit (16 %) due to disposal of wood ashes and the wastewater treatment plant (12 %) due to sludge spreading. In the TEP (total for biorefinery system: 11,54 kg 1,4-DCB/t cellulose) the co-generation process had the highest impact with a share of 57 % followed by the impact of the production of chemicals (27 %). Similar results were found for the acidification potential (total for biorefinery process: 5,2 kg SO_2 eq./t cellulose) with the main contribution coming from the co-generation unit (57 %) followed by the production of chemicals with a share of 22 %. Overall, the environmental impacts of the biorefinery system originated mainly from the production of chemicals and the on-site energy production by cogeneration.

2.4. LCA of nano-cellulose production

2.4.1. Overview nano-cellulose

Nano-cellulose is isolated cellulose with a nanometer size range, usually below 100 nm. Nowadays nano-cellulose has a wide spectrum of applications in areas like paper making, food, cosmetic and hygiene products or artificial blood vessels (Li et al., 2013).

Conventionally nano-cellulose is classified into three categories: Nano fibrillated cellulose (NFC, often also referred to as micro fibrillated cellulose (MFC)), nanocrystalline cellulose (NCC) or bacterial nano-cellulose (BNC). NFC is usually prepared from wood or other plant fibres via different treatments. The most common production route is a mechanical treatment (e.g. homogenization, sonification, blending) with an optional chemical pre-treatment (e.g. oxidation, carboxymethylation, acid or enzymatic hydrolysis) (Li et al., 2013).

2.4.2. LCA of nano-cellulose from woody biomass from a chemical-mechanical approach

Li et al. (2013) focussed in their study on the production of NFC at a laboratory scale comparing four different chemical-mechanical approaches applying a life cycle assessment method. The functional unit was 10 g dry nano-cellulose and the selected environmental impacts were CED, GWP, human health, ecosystem quality and resources (for the last three Eco-Indicator 99 with a hierarchist perspective was used). The examined system excluded the use and the disposal phase as they differed with every application of the nano-cellulose. The data of the extraction of the raw material was based on compiled LCAs. In Figure 2 the four different fabrication routes are shown. The first is TOSO (TEMPO-oxidation for chemical modification, sonication for mechanical disintegration), the second route is TOHO (TEMPO-oxidation for chemical modification, homogenization for mechanical disintegration), the third is CESO (chloroacetic acid etherification for chemical modification, sonication for mechanical disintegration) and the last route is CEHO (chloroacetic acid etherification for chemical modification, homogenization for mechanical disintegration) (Li et al., 2013).

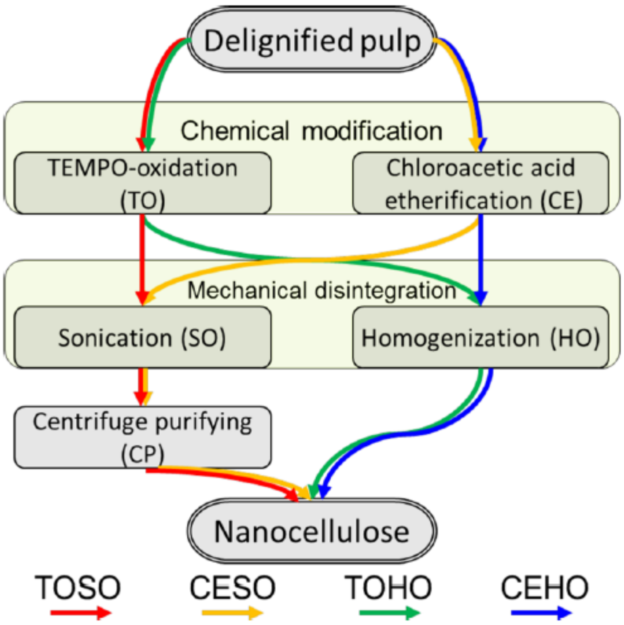

Figure 2: Illustration of the four different fabrication routes assessed (Li et al., 2013)

The TOHO route had the least cumulative energy demand (34,7 MJ compared to 64,9 – 176,1 for the others, all based on the functional unit) and GWP (190 kg CO_2 eq./kg nano-cellulose compared to up to 1.160 kg CO_2 eq./kg nano-cellulose). It must be mentioned that mechanical processes for sonication have a higher energy demand than the chemical ones, consequently sonication is probably not competitive with homogenization at an industrial level. For the other environmental impacts TOHO was also the lowest in each perspective. Further the Kraft pulp and NFC process were compared to understand the environmental impact increase by producing nano-cellulose from wood pulp. The Ecoinvent process “Sulphate pulp, average, at regional storage/RERU” was compared to the lowest impact process of NFC, therefore with TOHO. The CED value for pulp was 2,5 MJ compared to 34,7 MJ for NFC, the EI99 value for pulp was 7,4 mPt compared to 164 mPT for NFC. If the NFC process is upscaled to an industrial scenario the CED value is 10,6 MJ and EI99 value is 45 mPt (Li et al., 2013).

Turk et al. (2020) assessed the production of NFC from thermo-groundwood in a laboratory scale within the TOHO fabrication process. The specific steps were a Soxhlet extraction to extract cellulosic fibres from the used wood, delignification and removal of hemicelluloses, further chemical modification with TEMPO-oxidation followed by high-pressure homogenization for mechanical disintegration. The aim of the study was a hot-spot-analysis of the prosed chain, but also to compare three commonly used impact assessment methods (ILCD/PEF, CML 2001 and ReCiPe 2016) with its different impact categories (e. g. GWP, ODP, HTP or acidification potential). Turk et al. (2020) defined 1 kg of dry nano-cellulose as functional unit and a “cradle-to-gate” system boundary including production of the raw material, synthesis of chemicals and the fabrication of NFC in the laboratory. Since the production of NFC leads to two co-products (extractives and hemicellulose) allocation was done according to mass; even though lignin has a high calorific value it is usually burnt and therefore defined as waste. The study found the Soxhlet extraction to be the most environmentally burdening due to its relatively high energy and chemical demand, but it hast to be mentioned that this process was just used in a laboratory scale. Turk et al. (2020) stated that the environmental footprint could be reduced tremendously (60-85 %) by using an industrial production site. Further, considering the “cradle-to-gate” approach, the fabrication of NFC had the biggest impact during the examined life cycle

(Turk et al., 2020). This is consistent with the upcoming of Li et al. (2013) where the comparison between the production of NFC and the used wood pulp showed a higher environmental burden. The GWP found by Turk et al. (2020) was between 770 – 814 kg CO_2 eq. taking the three different impact assessments into accountant.

Arvidsson et al. (2015) ran another laboratory-scale study to produce NFC from wood pulp using a mechanical approach with different pre-treatments: an enzymatic, a carboxymethylation pre-treatment which is like the chloroacetic pre-treatment used from Li et al. (2013) and one without. Like Li et al. (2013) Arvidsson applied a "cradle-to-gate" approach (raw material extraction to the production of NFC in the laboratory), defined 1 kg nano-cellulose as functional unit and examined the CED, GWP, TAP and water depletion (WD) as impact categories with ReCiPe as impact assessment method. As starting material four different types of wood pulp from the Ecoinvent database were chosen: ECF sulfate, TCF sulfate, unbleached sulfate, which was chosen for the baseline scenario due to the lowest environmental impact, and chlorine bleached sulphite pulp which has the highest environmental impacts. The results showed that the fabrication route with the carboxymethylation pre-treatment had the highest impacts for all the categories, while the other two routes had similar magnitudes. The CED in the baseline scenario for the carboxymethylation route was ~1.800 MJ/kg nano-cellulose, for the enzymatic route ~100 MJ/kg nano-cellulose and for the no pre-treatment route ~200 MJ/kg nano-cellulose demonstrating way lower results than Li et al. (2013) who described for the TOHO fabrication process a CED of around 3.470 MJ/kg. The TAP in the baseline scenario was ~0,2 kg SO_2 eq./kg nano-cellulose for the carboxymethylation route and for the enzymatic and the no pre-treatment route ~0,01 kg SO_2 eq./kg nano-cellulose. The GWP in the baseline scenario was ~100 kg CO_2 eq./kg nano-cellulose for the carboxymethylation route and for the enzymatic and the no pre-treatment route below 5 kg CO_2 eq./kg nano-cellulose (Arvidsson, Nguyen and Svanström, 2015). These results are lower than the GWP stated by Li et al. (2013) with 190 kg CO_2 eq./kg. Though, it must be noted that Li et al. (2013) assumed a higher input of chemicals in their pre-treatment process which can lead to this high numbers (Arvidsson, Nguyen and Svanström, 2015). The water depletion in the baseline scenario for the carboxymethylation route was ~1 m^3/kg nano-cellulose, for the enzymatic route ~0,2 m^3/kg nano-cellulose and for the no pre-treatment route around 0,1 m^3/kg nano-cellulose. For the no pre-treatment route the main impacts were contributed from the NFC production (Arvidsson, Nguyen and Svanström, 2015) which is what Li et al. (2013) and Turk et al. (2020) also concluded. Further, Arvidsson et al. (2015) stated that reducing the electricity use in the treatment process is the easiest way to reduce environmental impacts of NFC.

Like Arvidsson et al. (2015) Nguyen et al. (2014) also performed an LCA of wood based NFC assessing an enzymatic and a carboxymethylation pre-treatment with a following homogenization treatment, defining 1 kg of dry NFC as functional unit, setting the system boundaries to include the extraction of the raw material to the processing of the NFC, excluding use and disposal phase. The aim of this master thesis was to assess the total energy use for the two different fabrication routes and to compare them to each other plus to point out the main factors that contribute to the energy demand (Nguyen, 2014). The used data of this master thesis built upon data from other studies (e.g. (Arvidsson, Nguyen and Svanström, 2015) and (Li et al., 2013)) and the results of the total energy consumption ranged from 90 MJ/kg for the best case, the enzymatic route, to 1.450 MJ/kg for the worst process, the carboxymethylation route. The lower energy consumption compared to Arvidsson et al. (2015) and Li et al. (2013) can be explained by the use of different pulp, different amounts of input chemicals and the use of different energy mixes.

Sun et al. (2013) performed an LCA using another chemical-mechanical approach to produce NFC by assessing the environmental burdens of a combined wet disk milling and mild hot-compressed water process. Again, a cradle-to-gate approach was used including the production of woody biomass and ending with the production of NFC excluding the use and disposal phase. 1 kg of dry NFC was defined as functional unit. The fabrication route was the following: planting and logging of the woody biomass, chipping, transportation to the NFC plant, dry powdering of the chips in a cut mill, wet cut milling in a wet cut mill and finally the hot-compressed water treatment in a wet disk mill to receive a nanoscale. The last step was done three to ten times, depending on the quality of the used material. As NFCs are often mixed with polypropylene (PP) to produce new composites, the study aimed to compare greenhouse gas emissions of NFC to PP production. Results showed a total energy consumption of 11,1 to 30,2 MJ/kg dry NFC, which is much lower compared to PP. Also, the GWP of NFC was between 1,26 to 3,68 kg CO_2 eq./kg (the wet disk milling process contributing 57-73 %

to it) which is in the range of 1,84 kg CO_2 eq./kg of PP (Sun et al., 2013) and is comparable to the findings of Arvidsson et al. (2015).

2.4.3. LCA of nano-cellulose from non-woody biomass from a chemical-mechanical approach

Piccinno et al. (2018) developed a method with five steps to scale-up a laboratory process to a larger scale. The researchers already assessed the environmental burdens of the lab-scale process of producing nano-cellulose from carrot waste and compared it to other lab-scale LCAs like Li et al. (2013) (Piccinno et al., 2015). While this comparison was possible due to the same scale, the results compared to competing materials like carbon or glass fiber produced in an industrial scale were not competitive. Therefore, the study in 2018 aimed to apply their method at the new fabrication process, hence assess it in a larger scale and again compare it to the competing materials. A cradle-to-gate approach was chosen, starting with either the whole carrot or the collection of carrot pomace and ending with the production of a GripX coated nano-cellulose yarn done by wet spinning, not including the use and disposal phase due to the many applications. 1 kg of nano-cellulose yarn was defined as the functional unit and the ReCiPe impact assessment method with a heuristic perspective was chosen. The comparison of the up-scaled process with the lab scale scenario showed a reduction in environmental impacts (factor 3 by the highest impact industrial scenario to factor 6,5 by the lowest impact scenario). When compared to competitive materials like carbon and glass fibres the production of 1 kg nano-cellulose yarn from carrot pomace performs somewhere in between these two (Piccinno et al., 2018).

2.5. Findings and research issue

The literature review of LCAs of biogas production from manure showed, that there are lots of studies comparing different substrates. In this thesis an integrated biogas system approach must be applied by using manure as raw material, further producing nano-cellulose from the digestate and get a by-product that can be used as fertilizer. The research showed that there is no study that used the approach at such an industrial level by combining biogas production with the further use of the digestate as a resource material for producing another product. Regardless, the found studies with an integrated system showed benefits compared to conventional ones.

The literature review of LCA of nano-cellulose production shows a lack of research in the industrial scale. The studies within a laboratory scale show different fabrication routes to produce nano-cellulose and different findings of environmental burdens and energy consumption depending on the pre-treatment and treatment.

Overall literature shows that there are studies that either assess the environmental burdens of biogas from manure or an integrated biogas system with further use of the biogas and heat or the production of NFC with different system boundaries and raw material (wood pulp or carrot waste).

No LCA study was found that covers a whole biorefinery producing biogas and heat with a further use of the solid fermentation residue as raw material input to produce NFC which is the objective of the present thesis

3. Objectives

Based on the research issue the following key topics will be covered:

The global aim of the thesis is to provide a comparative LCA at an industrial level between the production of nano-cellulose from

1) wood-based pulp → wood chips scenario
2) elephant manure that was first digested in a biogas plant → manure scenario

to assess the environmental impacts. Hence the following sub-goals must be executed:

- Literature research about LCAs of biogas, pulp and NFC production
- Aggregation of input data (primary and secondary)
- Research of used application in the industry scale and appropriate proxies
- Implementation of the LCA
- Sensitivity Analysis
- Evaluation of the results and comparison of the different systems
- Identification of the system with the lowest energy demand

This thesis is also intended to give a basis for further research of the production of nano-cellulose from manure from different animals, like cattle or pig.

4. Material and methods

To determine the ecological impacts of the production of biogas and nano-cellulose from manure, this study applies the method of life cycle assessment. In chapter 4.1 the life cycle assessment method with its four phases is described. Further, in chapter 4.2 the used software for the modelling and the supporting database are characterized. Chapter 4 also includes the model design, the description of all used input- and output-data for the Inventory analysis phase, the data collection and its quality and the used range of variation of the data.

4.1. The four phases of life cycle assessment

In general, an LCA approaches the subject of environmental aspects and potential environmental impacts of a product or service throughout its whole life cycle. The life cycle of an examined product or good starts with the acquisition of raw material, production, use, end-of-life treatment, recycling and final disposal (ISO 14040, 2006). Although the results can support product development and improvement, public policy making or marketing LCA might not be the best environmental management technique for all situations, because it does not address impacts in a social or economic aspect (ISO 14040, 2006). For this purpose, a life cycle cost assessment (LCCA) enables a monetary assessment by summing up all the real costs connected with the whole life cycle of the assessed product (Klöpffer and Grahl, 2009, p. 390). Further, to assess social aspects a social life cycle assessment (SLCA) can be conducted to focus on the human well-being (Klöpffer and Grahl, 2009, p. 392). All three pillars of sustainability are assessed in a life cycle sustainability assessment (LCSA) (Klöpffer and Grahl, 2009, p. 394).

In this thesis only ecological aspects will be addressed; economic or social aspects will be excluded. The norm that determines the methodological framework of an LCA is stated in the standards ISO 14040 (ISO 14040, 2006) and ISO 14044 (ISO 14044, 2006).

The four phases of an LCA that are defined in the ISO standards are

- the goal and scope definition,
- life cycle inventory analysis,
- life cycle impact assessment (LCIA), and
- interpretation (ISO 14040, 2006).

The framework of a life cycle assessment is illustrated in Figure 3.

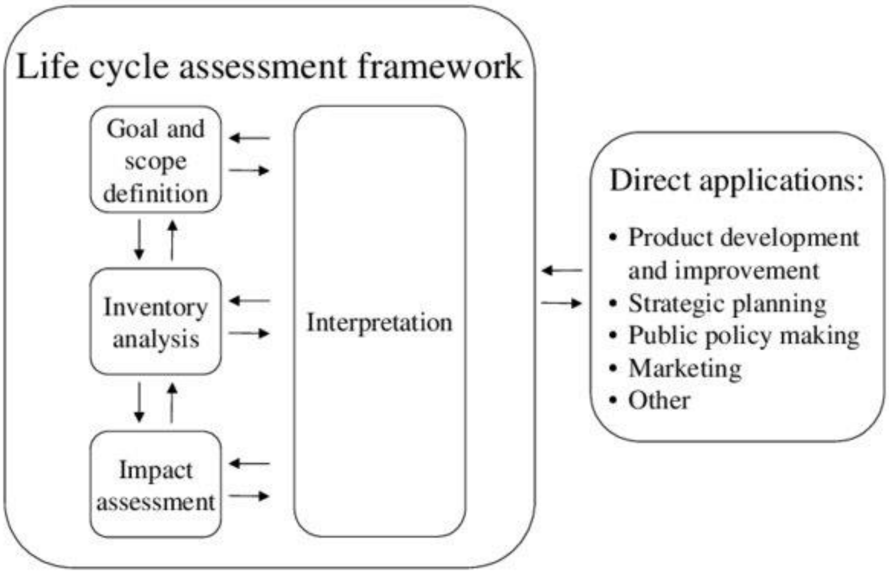

Figure 3: LCA framework (adapted from (ISO 14040, 2006))

The arrows in Figure 3 represent that a life cycle assessment is an iterative method, meaning the four phases are dependent on each other and not necessarily performed in a linear way. Results from one phase are used in other phases. This approach ensures comprehensiveness and consistency throughout the whole study, but also needs a high level of transparency to clear up the work (ISO 14040, 2006).

4.1.1. Goal and scope definition

In the first phase some essential classifications must be chosen that have a major influence on the further work progress. It is important to know the intended application and audience in order to determine a certain goal of the LCA. Depending on the goal the wide and depth, the functional unit, reference flow and system boundaries of the LCA are defined (ISO 14040, 2006).

4.1.2. Life cycle inventory (LCI) analysis

The second phase, the inventory analysis, mainly consists of data collection and quantification of all relevant inputs and outputs of the assessed system within the set system boundaries. The collected data includes energy, raw material and ancillary inputs, products, co-products, waste and emissions to the environment. If needed, allocation must be taken into account at this phase (ISO 14040, 2006).

4.1.3. Life cycle impact assessment (LCIA)

In the third phase, the life cycle impact assessment, the results from the LCI are used to associate the collected data with environmental impact categories and the corresponding category indicators. The elements of an LCIA are the selection of impact categories with the corresponding category indicators and characterization models, the classification of the LCI results, the calculation of the chosen category indicators and finally the LCIA profile (ISO 14040, 2006). The ISO norm 14040 (2006) states that the impact assessment can only address environmental burdens that are specified in the first phase of the LCA. The results of the calculation of the category indicators state their environmental impact per unit of stressor (e.g. per kg of resource used) (Goedkoop et al., 2013).

For the present thesis the used impact categories are detailly explained in chapter 4.3.

4.1.4. Interpretation

In the final step, the interpretation phase, the results from the LCI and LCIA are summarized and can be used as recommendation for decision-makers. Further, the scope of the LCA, the collected data and the results in relation to the goal and scope are analysed (ISO 14040, 2006).

4.2. Software and database

The used software in this thesis is openLCA version 1.9 which is an open source and free software from the company GreenDelta (Green Delta GmbH, 2018). Numerous free and paid databases can be imported into the software, making it a strong tool to perform an LCA.

For this thesis the Ecoinvent database version 3.6 was selected which was released in 2019. The Ecoinvent database includes around 17.000 datasets in many areas (e.g. energy supply, transport, biomaterials). Further the database has a high-quality control, all around the world partners to provide relevant data and regular updates which makes it one of the world's leading LCI database in terms of transparency and consistency (Ecoinvent Association, 2019).

The method ReCiPe2016 Midpoint (H) was used as impact assessment method within the Ecoinvent database (Goedkoop et al., 2013; Huijbregts et al., 2016). Usually a timeframe of 100 years is selected for this perspective which is also chosen for this master thesis (Goedkoop et al., 2013).

4.3. Impact categories studied

As described in chapter 4.1.3 the results of the life cycle inventory are assigned to different impact categories which represent environmental issues. Each impact category has its own category indicator which represents the category in a quantitative way (ISO 14040, 2006). The selection of the impact category must be consistent with the goal and scope of the LCA, as well as reflect as good as possible the environmental issues of the dealt with product system (ISO 14044, 2006).

Following, the analysed impact categories in this thesis are described:

Climate Change (GWP100)

The impact category climate change is referencing to the anthropogenic global warming by using the category indicator global warming potential (GWP). The foremost cause of this global warming is the emission of GHGs to the atmosphere leading to the greenhouse effect, other causes are for example changes in terrestrial albedo which is defined as the amount of solar radiation that is reflected by the surface of the earth or aerosol or soot emissions. All the causes of global warming have a special impact on radiative forcing (Levasseur, 2015). Levasseur (2015) defines the radiative forcing as "the perturbation of the Earth's energy balance". The GWP can be explained as the relation between the supplementary radiative forcing caused by the emission of 1 kg of a greenhouse gas to the supplementary radiative forcing caused by the release of 1 kg of CO_2 (Huijbregts et al., 2016). To compare different GHGs which can cause GWP a reference substance is used to compare these gases over a certain timespan. A kilogramme CO_2 to air equivalent (kg CO_2 eq.) is commonly used. This factor expresses the impact of a kilogramme of a GHG relative to the impact of one kilogramme of CO_2 to air (Goedkoop et al., 2013). However, since different GHGs have different tropospheric lifespans (e.g. Methane has a lifespan of 10 years), a specific timespan must be chosen. Usually, for live cycle assessments a time span of 100 years is selected. Corresponding GWP numbers can be found in the newest IPCC publications (Intergovernmental Panel on Climate Change) (Klöpffer and Grahl, 2009, p. 254f).

Further, Levasseur (2015) states that the foremost GHG coming from anthropogenic activities are carbon dioxide (CO_2), nitrous oxide (N_2O), methane (CH_4) and halocarbons.

For this thesis a time span of 100 years is chosen, therefore referring to the climate change impact category with the abbreviation GWP100.

Freshwater eutrophication potential (FEP)

Eutrophication can be best understood as excess supply of nutrients. This oversupply leads to increased upbuilding of biomass, e.g. increased growth of algae which can lead to a change of water quality and to a total change of the range of species. Basically, eutrophication can be divided in terrestrial and aquatic eutrophication. The aquatic eutrophication can then be further divided in marine and freshwater eutrophication. The most important nutrients for plants are phosphor and nitrogen, while phosphor is usually the limited nutrient in freshwater compartments and nitrogen the limited nutrient in the sea. In this impact category all incomplete degraded inputs to freshwater compartments are included with the assumption that every unintended input could lead to a harmful impact to the water body (Klöpffer and Grahl, 2009, p. 281pp). Emissions of ammonia, nitrates, nitrogen oxides and phosphor contribute especially to increasing eutrophication (Goedkoop et al., 2013). The unit of the freshwater eutrophication potential is 1 kg of phosphate equivalents (kg PO_4^{3-} eq.) (Klöpffer and Grahl, 2009, p. 284).

Fossil resource scarcity (FRS)

As fossil resources count crude oil, natural gas and coal. All these resources are theoretically regenerative, but since their recharge rate is slow and therefore periods of recharge time would be extremely long, they can be practically seen as non-regenerative. (Klöpffer and Grahl, 2009, p. 231 ff). It is assumed that the extraction of every additional unit of a fossil resource causes an impact of its scarcity on earth. As impact indicator for the fossil resource scarcity the surplus cost of such a resource is taken. The surplus cost expresses the additional future cost of the production of one additional unit of the fossil resource now (Ponsioen, Vieira and Goedkoop, 2014; Huijbregts et al., 2016).

For characterisation purpose the unit 1 kg of oil equivalent (kg oil eq.) is used (Goedkoop et al., 2013).

Terrestrial acidification potential (TAP)

Atmospheric deposition of different inorganic substances can lead to a change in pH value in soils, more precisely to a decrease in pH value. This decrease is a deviation from the optimum acidity of the soil and can lead to a loss of plant species. The most important emissions contributing to the terrestrial acidification potential are nitrogen oxides, ammonia and sulphur dioxide (Goedkoop et al., 2013; Huijbregts et al., 2016). The terrestrial acidification potential is expressed in kg sulphur dioxide equivalents (kg SO_2 eq.) (Huijbregts et al., 2016).

Impact categories relating to toxicity

The impact categories human toxicity and ecotoxicity are both dealing with potential ecotoxic impact of different chemicals (Huijbregts et al., 2016). The main difference between these categories are their safeguard subjects. For human ecotoxicity the individuum itself is the main focus, while ecotoxicity aims to save a whole ecosystem by not focussing on a specific species (Klöpffer and Grahl, 2009, p. 296). The potential ecotoxic impact of a chemical can be further investigated in the soil, freshwater or seawater leading to a division of the ecotoxicity to the three impact categories terrestrial, freshwater and marine ecotoxicity. The unit for the impact categories relating to toxicity is 1 kg of 1,4-dichlorobenzene (kg 1,4-DCB) (Goedkoop et al., 2013).

Human toxicity potential (HTP)

The impact category can be divided in carcinogenic (HCTP) and non-carginogenic (HNCTP) impacts, representing the change in lifetime disease incidences depending on a change of intake of certain chemicals (Huijbregts et al., 2016).

Terrestrial ecotoxicity potential (TEP)

The terrestrial ecotoxicity potential characterizes the change in the disappeared fraction of species in a certain ecosystem due to a change of concentration of a chemical (Huijbregts et al., 2016).

4.4. Data collection and quality

The data collection for this thesis contained a literature research about the state of knowledge and practical data of industrial applications, given data from experiments in a laboratory at the University of Natural Resources and Life Sciences and the University of Vienna and data from the Ecoinvent database version 3.6 (Ecoinvent Association, 2019).

4.4.1. Literature research

A profound literature research was done in order to figure out the state of the knowledge in the area of LCAs of nano-cellulose production, the industrial processes of pulp making and the practical basics of conducting a life cycle assessment.

For this literature research the search engines google scholar, ScienceDirect and the internal literature research database of the University of Natural Resources and Life Sciences were used.

4.4.2. Laboratory experiments

4.4.2.1. Chemical tests

The chemical tests were conducted by the Institute of Agricultural Engineering at the University of Natural Resources and Life Sciences in collaboration with the Department of Materials Chemistry at the University of Vienna.

The raw and the fermented elephant manure (0, 5, 10, 20, 30, 40 days fermented) were analysed regarding cellulose, hemicellulose and lignin content. The Van Soest method was used to analyse the fiber fractionation (Goering and Van Soest, 1970).

To prepare the samples they were dried and then treated in a Retsch Cryomill (shown in Figure 4) with liquid nitrogen to receive fine milled samples. A sample and the grinding balls are enclosed together in a round grinding vessel. During the grinding process the jar is cooled continually with liquid nitrogen and it radial oscillates in a horizontal position. Due to the oscillation the grinding balls pulverize the sample by simultaneously preserving volatile components (Retsch GmbH, 2020).

All samples were cooled down for 2 minutes at 5 Hz, and then continually cooled for 14 minutes at 28 Hz.

Figure 4: Used Retsch Cryomill to finely mill the samples via cryogenic grinding

After the cryogenic grinding neutral detergent fibre (NDF), acid detergent fibre (ADF) and originating from the ADF results acid detergent lignin (ADL) analyses were done in triplicates to determine cellulose, hemicellulose and lignin.

Neutral detergent fibre analysis:

0,5 g of each grinded sample was mixed with 50 ml of NDF solution (30 g neutral detergent solution, 5 ml triethylene glycol and 500 ml water), 1 ml of decahydronaphtalin and 0,25 g of sodium sulphite and cooked in the Buchi SpeedDigester K-439 for an hour. After cooking, the cooled samples were vacuum filtered as seen in Figure 5, then washed with hot water and acetone until the runoff was colourless. Afterwards, the filter crucibles were put in a drying oven until weight stability is reached, respectively (Van Soest and Wine, 1967).

Figure 5: Vacuum filtration of a sample

Acid detergent fibre analysis:

0,5 g of each grinded sample was mixed with 50 ml of ADF solution (10 g acid detergent solution in 0,5 Mol sulphuric acid) and 0,5 ml of decahydronaphtalin and cooked in the Buchi SpeedDigester K-439 for an hour. After cooking, the cooled samples were vacuum filtered, washed with hot water and acetone until the runoff was colourless. Afterwards, the filter crucibles were put in a drying oven until weight stability is reached and finally weighed, respectively (Goering and Van Soest, 1970).

Acid detergent lignin analysis:

For this analysis the remains of the filtrate of the ADF analysis were used. 8 ml of 72 % sulphuric acid were added to the filter crucibles, respectively, and stirred carefully. 7 ml of sulphuric acid were added, respectively. For 3 hours the filtrate was stirred every 30 minutes (see Figure 6) afterwards washed with water until the pH was between 6 to 7. The filter crucibles were put in a drying oven until weight stability is reached. Then the samples were placed in a muffle furnace at 500 °C for five hours. Finally, the filter crucibles were weighed, respectively (Goering and Van Soest, 1970).

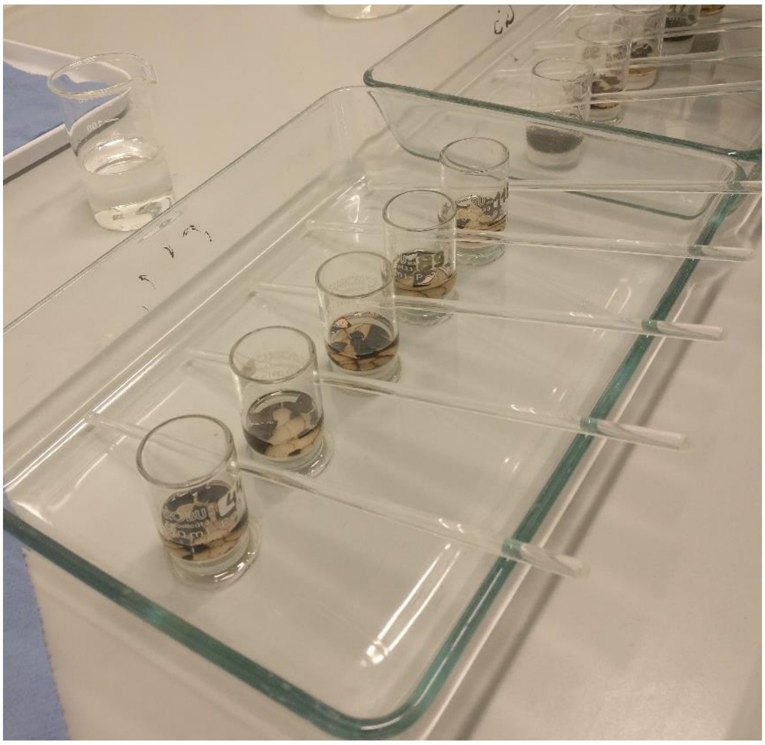

Figure 6: Filter crucibles with samples and sulphuric acid

With the results of the three analysis the hemicellulose, cellulose and lignin content can be determines as followed:

- Hemicellulose = NDF – ADF
- Cellulose = ADF – ADL

- Lignin = ADL

The sum of NDF, ADF and ADL does not give 100 % since there is also some organic material in the samples (Goering and Van Soest, 1970).

The results present a hemicellulose content of 33 wt%, cellulose content of 36 wt% and a lignin content of 18 wt%.

4.5. Model design

In this chapter the two product systems named manure scenario and wood chips scenario that are compared within the LCA are detailly explained. This includes the upscaling from the laboratory to an industrial scale, the inputs and outputs of every product system and other definitions. The exact values for all the input data are detailly shown in chapter 4.6.

4.5.1. Functional unit

According to the ISO 14040 (2006) "the primary purpose of a functional unit is to provide a reference to which the inputs and outputs are related." The definition of the functional unit ensures the comparability of different systems (of the same functional unit) (Klöpffer and Grahl, 2009, p. 4).

For this master thesis the functional unit is defined as 1 kg of dry nano-cellulose.

4.5.2. Manure scenario

4.5.2.1. Laboratory fabrication route

The method to produce nano-cellulose from elephant manure was invented from the Institute of Agricultural Engineering at the University of Natural Resources and Life Sciences in collaboration with the Department of Materials Chemistry at the University of Vienna. The data were created through profound experiments. In Figure 7 the overview of the process chain of the laboratory procedure is shown.

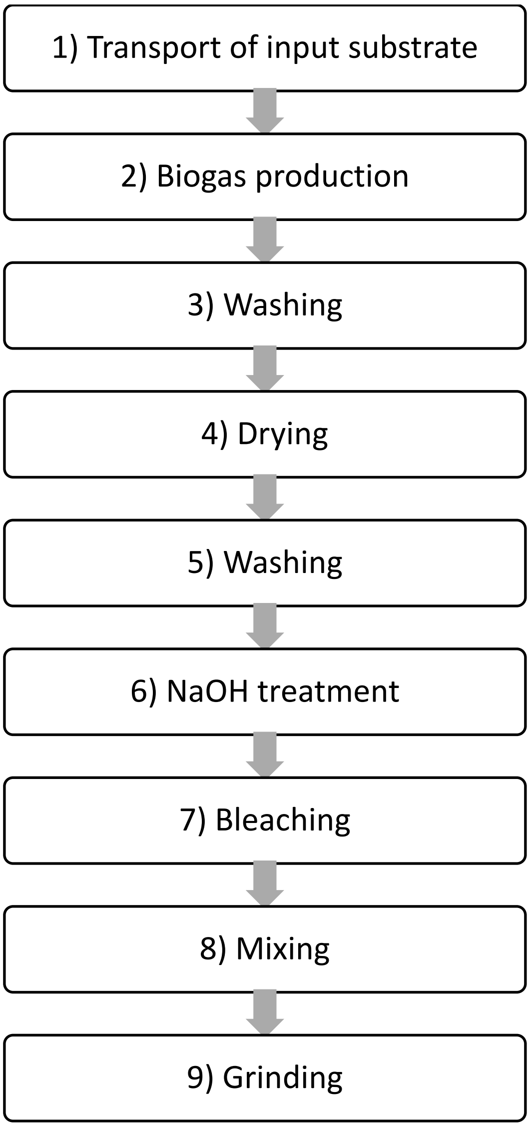

Figure 7: Overview laboratory process chain of the manure scenario

The method starts with the transportation of the manure from Tiergarten Schönbrunn to the biogas laboratory to produce biogas and heat. The manure and 200 mL of the used inoculum, which consists of two inocula from a biogas plant located in Margarethen am Moos, Austria, are filled in a eudiometer batch fermenter in a ratio 3:1 based on the volatile solid content. The mixture is stirred continuously at 37,5 °C lasting several time ranges (5, 10, 20, 30 and 40 days) and the biogas and methane production are monitored daily. One sample of manure (the reference) is not anaerobically digested to compare results between the fermented and the pure manure. All samples are washed thoroughly with distilled water and are subsequently dried at 40 °C to sterilize and preserve them for further use.

The dried samples are then washed three times with distilled water and a sieve to get rid of impurities like sand and stones via sedimentation. For the NaOH treatment a stirring plate is heated up to 80 °C, then 20 g dry mass of each manure sample and a 0,1 M NaOH solution are heated at consistent temperature for 2 h. The mixture is then filtered and washed by using a sieve until neutral pH to separate a liquid alkalic phase and a solid phase, the cellulosic fibres, that are further utilized.

Subsequently, the bleaching step is conducted with a 0,4 M sodium hypochlorite (NaOCl) solution for 17 h on a stirring plate at room temperature. Once more the mixture is washed by using a sieve until the smell of chlorine is not detectable anymore.

To finally produce nano-cellulose the samples are first passed through a mixer, then through a disk mill with supplementary water either 1, 2, 5, 7 or 10 times.

4.5.2.2. Up-scaling process

Lab-scale data which are used in LCAs frequently lead to much higher environmental impacts compared to industrialized processes due to the optimized use of material, energy or other inputs. Therefore, the comparison between lab-scale data and industrial data does not lead to a realistic result. By up-scaling the laboratory process to a commercial scale the environmental impacts can be drastically decreased (Piccinno et al., 2016). The challenge is to compare two fabrication routes of a product at an industrial level, while one process is just performed at a laboratory scale. In order to compare the two fabrication routes at a same level of maturity, a prospective approach is needed. According to Arvidsson et al. (2017) an LCA is defined as prospective "when the emerging technology studied is in an early stage of development, but the technology is modelled at a future, more-developed stage." The in chapter 4.5.2.1 explained laboratory process is not yet available at an industrial scale which leads to the need of a prospective approach. Thonemann et al. (2020) reviewed prospective LCAs and came up with four major challenges in conducting such an LCA: comparability, scaling difficulties, data availability and uncertainty. Especially the data availability is a challenge since no or just few data for generating an accurate life cycle inventory is available.

Parvatker and Eckelman (2019) analysed and compared different methods to estimate missing life cycle inventory data for chemicals: process simulation, detailed process calculations, basic process calculations, molecular structure-based models, stoichiometry and using proxy data. The comparison resulted in a recommendation showed in Figure 8 which method should be chosen for what purpose and how accurate these estimations are.

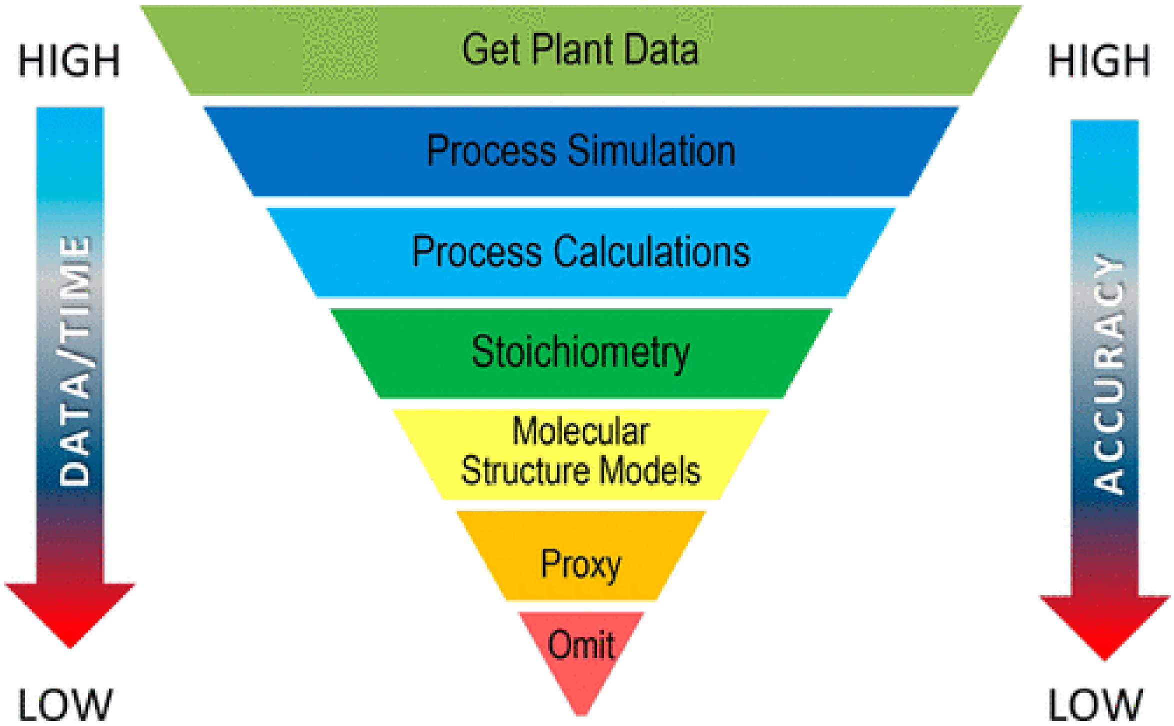

Figure 8: Hierarchy of methods used in estimating missing LCI data with respect to the data/time requirements and accuracy (Parvatker and Eckelman, 2019)

Although, the Proxy method is the second to last in accuracy compared to the other methods, it can be as accurate and even faster if the proxy is well chosen. If the proxy data set is complete, this method provides a first good estimation of environmental impacts. Still, in the long term, proxy data sets should be replaced by more accurate data when available to precise the results (Parvatker and Eckelman, 2019).

The present master thesis aims to compare two approaches of producing nano-cellulose with intermediate products at different stages of technology maturity. In the manure scenario a novel approach is used: elephant manure is fermented in a biogas plant, then used to produce a pulp-like product as last intermediate before nano-cellulose production. The wood chips scenario uses the mature technology of kraft pulping to produce wood pulp and finally nano-cellulose. Since the chemical treatment of the fermented elephant manure is alike to the pulp production the proxy method is chosen to estimate missing data for upscaling the manure scenario.

For performing this prospective LCA the following assumptions are applied:

- A biogas plant is used as proxy for the biogas production in the laboratory,
- a non-integrated pulp mill using softwood as starting material is the proxy for the pulp-like intermediate.

The biogas plant is modelled based on Kral et al. (2016), while for the non-integrated pulp mill the dataset “sulfate pulp production, from softwood, bleached” from the Ecoinvent database is used (Ecoinvent Association, 2019). No accurate proxy was found in the Ecoinvent database for the nano-cellulose production through mixing and grinding, though it can be assumed that the mixing step is already present in the pulp production. Especially, since the mixing step is just a preparation step for the grinding step. Therefore, the grinding step will be modelled for both scenarios in the laboratory scale based on primary data for each scenario. In Figure 9 the upscaling with the proxy approach is shown.

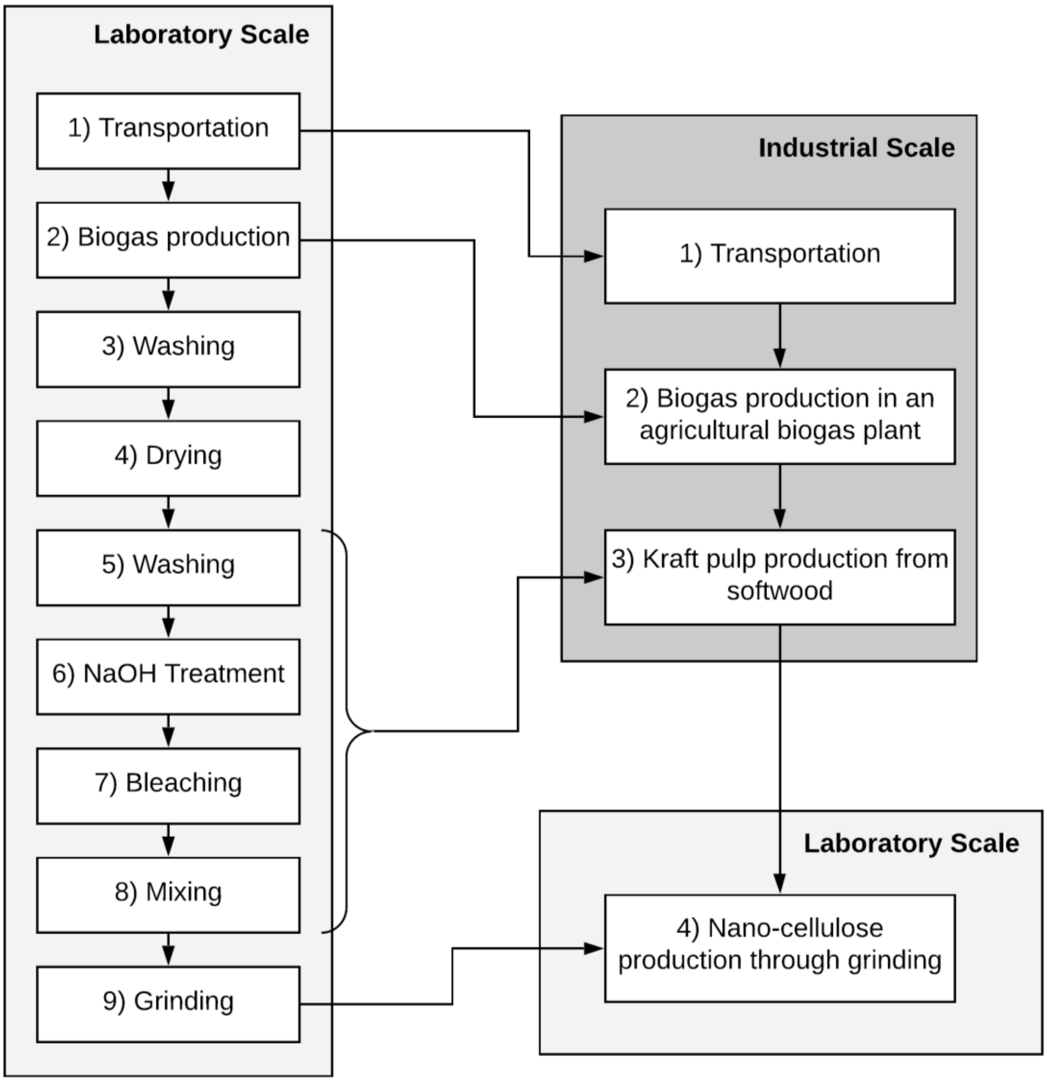

Figure 9: Using the proxy approach to upscale the manure scenario from laboratory scale to the industrial scale with no intermediate storage which outdates step 3 and 4

The assumption was made that the industrial site hosts all fabrication steps without storing intermediate products and it is assumed that the pulp production is conducted in one facility.

Since the shown sub-process of the laboratory fabrication route 4) “drying” is for the purpose of preserving and the industrial site hosts no storing of intermediate products, this step is no longer required at the commercial scale. Sub-process 3) “washing” is also no longer required to avoid two washing steps.

4.5.2.3. System boundaries and system diagram

With a system diagram it is possible to present a product system in an illustrated way. It shows all analysed unit processes and their interactions among each other through product flows or with the environment through elementary flows. Flows are illustrated as arrows (Klöpffer and Grahl, 2009, p. 29). By choosing system boundaries it is specified which processes are analysed in the life cycle assessment (ISO 14040, 2006) and which ones are beyond the scope of a study.

In Figure 10 the system diagram of the manure scenario is illustrated. The dashed line marks the system boundaries of the product system. The construction material for both the biogas plant and the pulp factory are inside the system boundaries which also includes the transport of the material. Also, the transport for all used chemicals is analysed. Since elephant manure is considered as by-product or even waste and not as a primary benefit in elephant keeping, all environmental impacts are allocated to keeping these animals. Therefore, no upstream environmental burden is considered for elephant manure.

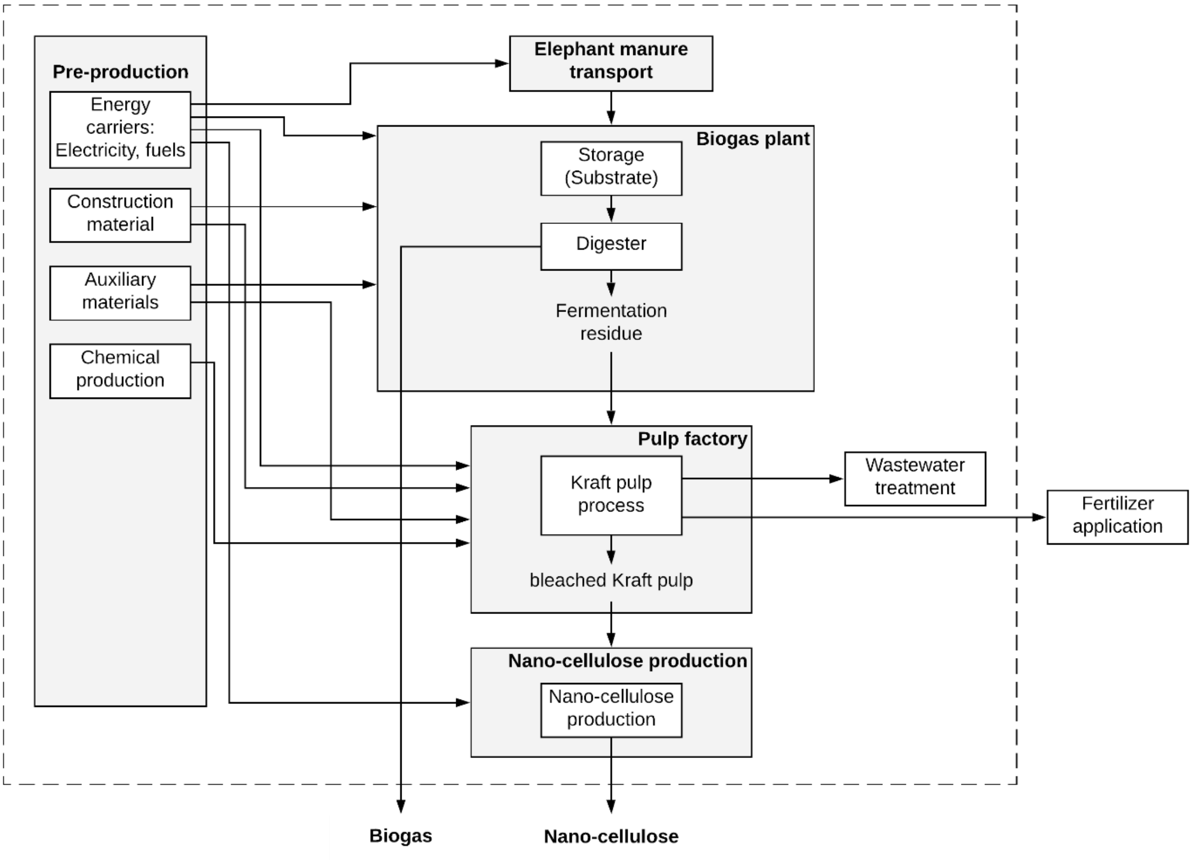

Figure 10: System diagram of the manure scenario with the fertilizer application being beyond the scope

Elephant manure transport:

It is assumed that the elephant manure is collected from Tiergarten Schönbrunn and transported over 3 – 5 km to the industrial production site.

Loading and unloading of the manure on and off the truck is assumed to be negligible as diesel consumption and burning is most of the environmental burden.

Biogas plant:

The lifespan of the biogas plant is 15 years. The fermenter construction materials concrete, crushed rocks and asphalt are assumed to be transported for 30 km, reinforcement steel for 770 km (Kral et al., 2016). The fermenter of the biogas plant is assumed to be the same for both the manure and the wood chips scenario. They just differ in the input material, the emissions and use of fermentation residue.

For the needed input material of around 17.122 t FM of elephant manure per year 261 - 331 elephants are needed, assuming one elephant produces 140 – 180 kg of manure per day (online Focus, 2011).

Since elephant manure has a dry matter (DM) content of 22,4 % the material is diluted with water to 9,7 % dry matter content to make it pumpable for the feeding and to reach better stirring during the wet fermentation (Fachagentur nachwachsende Rohstoffe, 2016).

The biogas plant produces 1.229.177,02417 Nm³/a biogas referring to the organic dry matter (oDM) content of the input material, the methane content in the biogas is 60,72 % according to laboratory experiments at the University of Natural Resources (detailed data can be found in Appendix I). From the produced methane 0,2 % are assumed to be emitted to the atomosphere via fermenter leakages (Bachmaier, 2012). Further, 63,72 % of the organic material is degraded during the fermentation, leading to a total of 37.206,58458 t/a of fermentation residue with a dry matter content of 4,41 % and organic dry matter content of 3,31 %.

Exact calculations can be found in Appendix I.

Pulp factory:

For the process pulp production the Ecoinvent process “sulfate pulp production, from softwood, bleached” (Ecoinvent Association, 2019) is used. In the process the softwood as input material is changed to the fermentation residue from elephant manure.

Since the fermentation residue is used with an organic dry matter content of 3,31 % which is more fluid than the normally used softwood, wastewater and some inorganic suspended solids are included as additional outputs after the preparation for the cooking with the pulping chemicals.

Nano-Cellulose production:

The used data was provided by the Department of Materials Chemistry at the University of Vienna. The dry matter content was determined by using a drying oven, the electrical demand of the grinding was measured with a three-phase current Swissnox SX-3M (Blaufaktor GmbH & Co. KG, s.a.) power meter.

4.5.3. Wood chips scenario

The wood chips scenario consists of two big parts: the production of nano-cellulose from wood chips and, to create equal benefits of the two scenarios, also the production of biogas. To model a typical Austrian biogas facility maize silage and pig slurry are chosen as input material (Hopfner-Sixt, 2005).

4.5.3.1. System boundaries and system diagram

In Figure 11 the system diagram of the Wood Chips Scenario is illustrated. The dashed line marks the system boundaries of the product system. The construction material for both the biogas plant and the pulp factory are inside the system boundaries which also includes the transport of the materials. Also, the transport for all used chemicals is analysed. The upstream chains for both the production of the maize silage as input material for the biogas plant and forestry due to hardwood production as basis for the pulp production are inside the system boundaries.

In order to assess a common basket of benefits the same amount of biogas is used as additional input into the system that is produced in the manure scenario with the biogas plant by fermenting elephant manure referring to the functional unit of 1 kg of nano-cellulose.

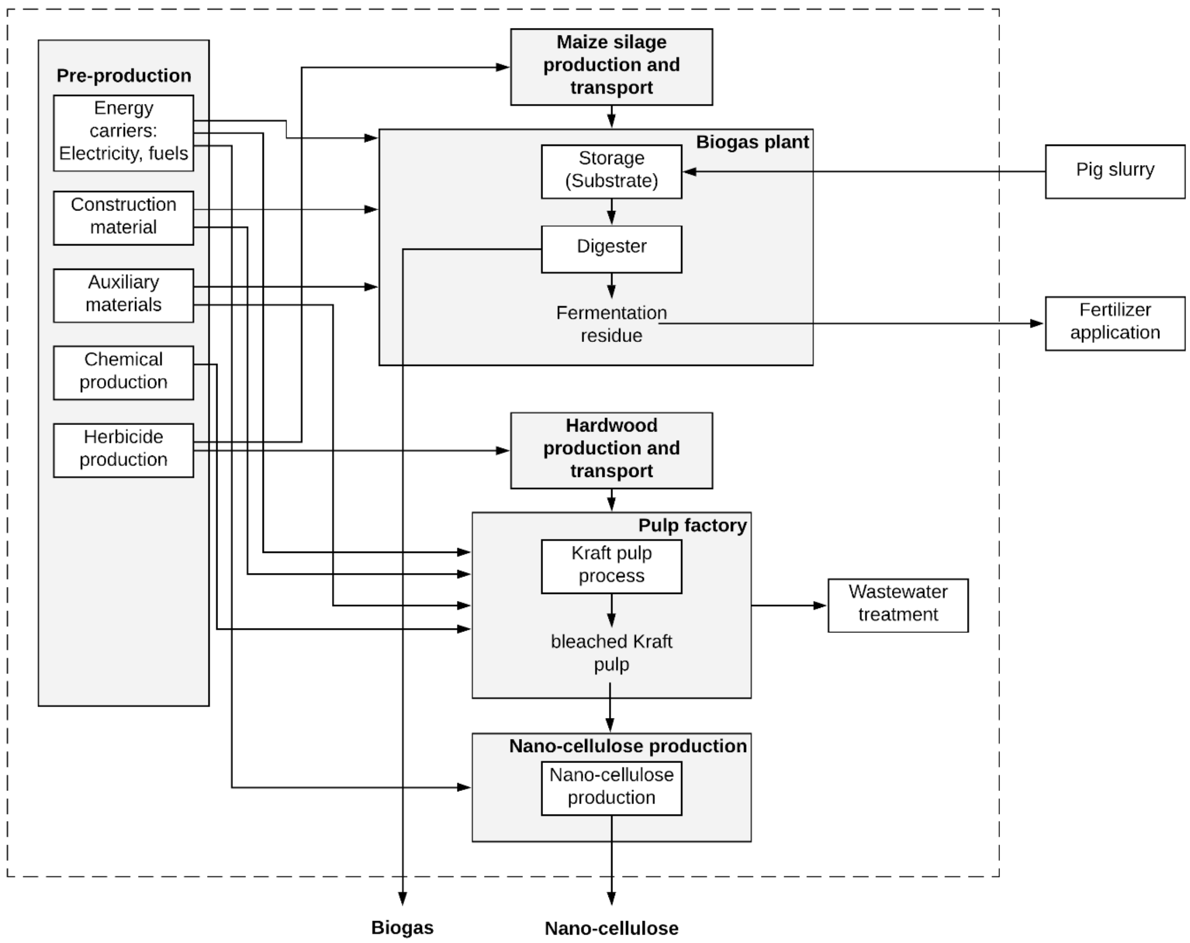

Figure 11: System diagram of the wood chips scenario with the fertilizer application and the pig slurry production being beyond the scope

Maize silage production and transport:

For the maize silage production, the process described in Kral et al. (2016) is used. This process is based on the Ecoinvent process “maize silage production, Swiss integrated production, intensive” (Ecoinvent Association, 2019) but the inputs, outputs and emissions are adjusted to Austrian conditions. The transport and other emissions occurring during the maize silage production are based on unpublished data from the University of Natural Resources from the institute of agricultural engineering and are therefore not displayed.

Biogas plant:

The lifespan of the biogas plant is 15 years. The fermenter construction material concrete, crushed rocks and asphalt are assumed to be transported for 30 km, reinforcement steel for 770 km (Kral et al., 2016).

As input material 70 % maize silage (33 % dry matter content) and 30 % pig slurry (6 % dry matter content) are used, percentages are referring to fresh matter (FM).

The biogas plant produces on average 2.211.522,61828 Nm³/a biogas referring to the organic dry matter content of the input material, the methane content in the biogas is on average 53,43 %. From the produced methane 0,2 % are assumed to be emitted through fermenter leakages (Bachmaier, 2012). Further, 78 % of the organic material is degraded during the fermentation, leading to a total of 12.287,89112 t/a of fermentation residue with a dry matter content of 8,29 % and organic dry matter content of 6,44 %. The fermentation residue is used as fertilizer. The application of this fertilizer is not within the default system boundaries, but is closer assessed in a sensitivity analysis in chapter 4.6.2.

Exact calculations can be found in Appendix II.

Pulp factory:

For the pulp production the Ecoinvent process "sulfate pulp production, from hardwood, bleached" (Ecoinvent Association, 2019) is used.

Nano-cellulose production:

The used data was provided by the Department of Materials Chemistry at the University of Vienna. The dry matter content was determined by using a drying oven, the electrical demand of the grinding was measured with a three-phase current Swissnox SX-3M (Blaufaktor GmbH & Co. KG, s.a.) power meter.

4.6. LCA input data, statistics and sensitivity analysis

This chapter provides an overview of the life cycle inventories of both scenarios, the probability distribution of the used data, the statistical analysis and the implemented sensitivity analysis.

4.6.1. Life cycle inventories with probability distribution

The ISO 14044 (2006) provides requirements for the quality of the data used in a life cycle assessment. One of the requirements is the precision of the used data, meaning the measures of the variability, e.g. the variance. Therefore, not only the mean value is used as input data, but also some probability distribution. The used data from the Ecoinvent database usually have a lognormal probability distribution (Ecoinvent Association, 2019), the concerning processes for every scenario individually are listed in the chapters below.

The processes that are newly modelled have different probability distributions based on their reference or on own calculations. An overview over the input data is given for every scenario individually in the chapters below.

4.6.1.1. Manure scenario

The used processes from the Ecoinvent database for the manure scenario are the following:

- Heat supply for the biogas plant: market for heat, district or industrial, other than natural gas
- Electricity supply for the biogas plant: market for electricity, medium voltage | electricity, medium voltage
- Pulp production from elephant manure is based on the Ecoinvent process sulfate pulp production, from softwood, bleached with additional inputs described in Table 1 (Ecoinvent Association, 2019)

These processes are adopted from the Ecoinvent database with their probability distribution, which is lognormal for all here used inputs and outputs.

In Table 1 all used inputs and outputs of the newly modelled or changed processes within the system boundaries, their probability distribution and their references are listed.

Table 1: Life cycle inventory of newly modelled or changed processes of the manure scenario

Process	Input/Output	Category	Probability distribution	mean; min-max	Unit	Standard Deviation	Reference
Transport	Input	transport, freight, lorry 16-32 metric ton, EURO5	Uniform	min: 3,00 max: 5,00	t*km		own assumption
Transport	Output	Elephant Manure		1,00	t		own assumption
Concrete transport	Input	Concrete		0,42	m³		Kral et al. (2016)
Concrete transport	Input	transport, freight, lorry 16-32 metric ton, EURO5		30,00	t*km		Kral et al. (2016)
Concrete transport	Output	Concrete		0,42	m³		Kral et al. (2016)
Mastic asphalt transport	Input	Mastic asphalt		1,00	t		Kral et al. (2016)
Mastic asphalt transport	Input	transport, freight, lorry 16-32 metric ton, EURO5		30,00	t*km		Kral et al. (2016)
Mastic asphalt transport	Output	Mastic asphalt		1,00	t		Kral et al. (2016)
Reinforcing steel transport	Input	Reinforcing steel		1,00	t		Kral et al. (2016)
Reinforcing steel transport	Input	transport, freight, lorry 16-32 metric ton, EURO5		770,00	t*km		Kral et al. (2016)
Reinforcing steel transport	Output	Reinforcing steel		1,00	t		Kral et al. (2016)
Crushed rocks transport	Input	Crushed rocks		1,00	t		Kral et al. (2016)

Crushed rocks transport	Input	transport, freight, lorry 16-32 metric ton, EURO5		30,00	t*km		Kral et al. (2016)
Crushed rocks transport	Output	Crushed rocks		1,00	t		Kral et al. (2016)
Chromium steel 18/8 transport	Input	Chromium steel 18/8		1,00	t		Kral et al. (2016)
Chromium steel 18/8 transport	Input	transport, freight, lorry 16-32 metric ton, EURO5		770,00	t*km		Kral et al. (2016)
Chromium steel 18/8 transport	Output	Chromium steel 18/8		1,00	t		Kral et al. (2016)
Biogas plant construction	Input	Concrete	Normal	2.108,33	m³	210,83	Kral et al. (2016)
Biogas plant construction	Input	Mastic asphalt	Normal	1.456,31	t	145,63	Kral et al. (2016)
Biogas plant construction	Input	Reinforcing steel	Normal	87,70	t	8,77	Kral et al. (2016)
Biogas plant construction	Input	Crushed rocks	Normal	24.000,00	t	2.400,00	Kral et al. (2016)
Biogas plant construction	Input	Chromium steel 18/8	Normal	2,00	t	0,20	Kral et al. (2016)
Biogas plant construction	Output	Biogas plant		1,00	Number of items (biogas plant; lifespan 15 a)		Kral et al. (2016)
Biogas production	Input	Biogas plant construction material		0,067	Number of items (biogas plant)		Kral et al. (2016)

Biogas production	Input	Electricity from grid (medium voltage)	Logarithmic normal distribution	498,00	MWh/a	1,00 (geometric standard deviation; GSD)	Kral et al. (2016)
Biogas production	Input	Thermal energy	Logarithmic normal distribution	458,73	MWh/a	1,00 (GSD)	Kral et al. (2016)
Biogas production	Input	Elephant manure		17.122,70	t FM/a		own calculation, data based on Kral et al. (2016), further information in Appendix I
Biogas production	Input	Water		22.259,50	t/a		own calculation, further information in Appendix I
Biogas production	Output	Biogas	Normal	1.229.177,02	Nm³/a	38.491,94	own calculation, further information in Appendix I
Biogas production	Output	Methane from Fermenter leakages	Normal	980,78	kg/a	46,19	own calculation, data based on Kral et al. (2016) & Bachmaier (2012), further information in Appendix I
Biogas production	Output	Fermentation Residue		37.206,58	t/a		own calculation, further information in Appendix I

Pulp production	Input	Fermentation Residue		55,10	kg		own calculation, further information in Appendix I
Pulp production	Output	Water (Emission to water)		52,65	kg		own calculation, further information in Appendix I
Pulp production	Output	Suspended solids, unspecified		0,62	kg		own calculation, further information in Appendix I
Pulp production	Output	sulfate pulp, from elephant manure, bleached		1,00	kg		data based on Ecoinvent Association (2019)
Nano-cellulose production	Input	Water		400,00	ml		Lab data (2019)
Nano-cellulose production	Input	Pulp		50,00	g		Lab data (2019)
Nano-cellulose production	Input	Electricity (medium voltage)		0,30	kWh		Lab data (2019)
Nano-cellulose production	Output	Nano-Cellulose		35,00	g		Lab data (2019)

4.6.1.2. Wood chips scenario

The used processes from the Ecoinvent database for the wood chips scenario are the following:

- Heat supply for the biogas plant: market for heat, district or industrial, other than natural gas
- Electricity supply for the biogas plant: market for electricity, medium voltage | electricity, medium voltage
- Pulp production from wood chips based on the Ecoinvent process sulfate pulp production, from hardwood wood chips, bleached with additional inputs described in Table 2 (Ecoinvent Association, 2019)

These processes are adapted from the database with their probability distribution, which is in this case lognormal for all inputs and outputs.

In Table 2 all used inputs and outputs of the newly modelled or changed processes within the system boundaries, their probability distribution and their references are listed.

Table 2: Life cycle inventory of newly modelled or changed processes of the wood chips scenario

Process	Input/Output	Category	Probability distribution	mean; min-max	Unit	Standard Deviation	Reference
Application of liquid fermentation residue	Input	Fermentation Resdiue_empty		1,00	kg		Kral et al. (2016)
Application of liquid fermentation residue	Input	liquid manure spreading, by vacuum tanker		1,00E-03	m^3		Kral et al. (2016)
Application of liquid fermentation residue	Output	Ammonia to air		9,70E-04	kg		Kral et al. (2016)
Application of liquid fermentation residue	Output	Application of liquid fermentation residue		1,00	kg		Kral et al. (2016)
Application of liquid fermentation residue	Output	Dinitrogen monoxide to air		1,08E-05	kg		Kral et al. (2016)
Application of liquid fermentation residue	Output	Methane, non-fossil to air		3,26E-06	kg		Kral et al. (2016)
Maize silage production	Input	[thio]carbamate-compound		1,57E-06	kg		Kral et al. (2016)
Maize silage production	Input	Application of liquid fermentation residue		0,93	kg		Kral et al. (2016)
Maize silage production	Input	application of plant protection product, by field sprayer		1,63E-05	m^2		Kral et al. (2016)
Maize silage production	Input	chopping, maize		1,63E-05	m^2		Kral et al. (2016)

Maize silage production	Input	Energy, gross calorific value, in biomass		5,31	MJ		Kral et al. (2016)
Maize silage production	Input	fodder loading, by self-loading trailer		4,00E-03	m³		Kral et al. (2016)
Maize silage production	Input	hoeing		1,63E-05	m²		Kral et al. (2016)
Maize silage production	Input	maize seed, Swiss integrated production, at farm		4,40E-03	kg		Kral et al. (2016)
Maize silage production	Input	metolachlor		1,53E-05	kg		Kral et al. (2016)
Maize silage production	Input	pesticide, unspecified		1,06E-05	kg		Kral et al. (2016)
Maize silage production	Input	pesticide, unspecified		5,13E-06	kg		Kral et al. (2016)
Maize silage production	Input	sowing		1,63E-05	m²		Kral et al. (2016)
Maize silage production	Input	tillage, harrowing, by spring tine harrow		3,25E-05	m²		Kral et al. (2016)
Maize silage production	Input	tillage, ploughing		1,63E-05	m²		Kral et al. (2016)
Maize silage transport	Input	Maize silage		1,00	kg		
Maize silage transport	Input	Transport, freight, lorry unspecified	Logarithmic normal distribution	5,83E-02	t*km	1,41	Ecoinvent Association (2019)
Maize silage transport	Input	Transport, freight train	Logarithmic normal distribution	8,82E-03	t*km	1,41	Ecoinvent Association (2019)
Maize silage transport	Output	Maize silage		1,00	kg		Kral et al. (2016)
Concrete transport	Input	Concrete		0,42	m³		Kral et al. (2016)

Concrete transport	Input	transport, freight, lorry 16-32 metric ton, EURO5		30,00	t*km		Kral et al. (2016)
Concrete transport	Output	Concrete		0,42	m³		Kral et al. (2016)
Mastic asphalt transport	Input	Mastic asphalt		1,00	t		Kral et al. (2016)
Mastic asphalt transport	Input	transport, freight, lorry 16-32 metric ton, EURO5		30,00	t*km		Kral et al. (2016)
Mastic asphalt transport	Output	Mastic asphalt		1,00	t		Kral et al. (2016)
Reinforcing steel transport	Input	Reinforcing steel		1,00	t		Kral et al. (2016)
Reinforcing steel transport	Input	transport, freight, lorry 16-32 metric ton, EURO5		770,00	t*km		Kral et al. (2016)
Reinforcing steel transport	Output	Reinforcing steel		1,00	t		Kral et al. (2016)
Crushed rocks transport	Input	Crushed rocks		1,00	t		Kral et al. (2016)
Crushed rocks transport	Input	transport, freight, lorry 16-32 metric ton, EURO5		30,00	t*km		Kral et al. (2016)
Crushed rocks transport	Output	Crushed rocks		1,00	t		Kral et al. (2016)
Chromium steel 18/8 transport	Input	Chromium steel 18/8		1,00	t		Kral et al. (2016)
Chromium steel 18/8 transport	Input	transport, freight, lorry 16-32 metric ton, EURO5		770,00	t*km		Kral et al. (2016)
Chromium steel 18/8 transport	Output	Chromium steel 18/8		1,00	t		Kral et al. (2016)
Biogas plant construction	Input	Concrete	Normal	2.108,33	m³	210,83	Kral et al. (2016)
Biogas plant construction	Input	Mastic asphalt	Normal	1.456,31	t	145,63	Kral et al. (2016)
Biogas plant construction	Input	Reinforcing steel	Normal	87,70	t	8,77	Kral et al. (2016)
Biogas plant construction	Input	Crushed rocks	Normal	24.000,00	t	2.400,00	Kral et al. (2016)

Biogas plant construction	Input	Chromium steel 18/8	Normal	2,00	t	0,20	Kral et al. (2016)
Biogas plant construction	Output	Biogas plant		1,00	Number of items (biogas plant, lifespan 15 a)		Kral et al. (2016)
Biogas production	Input	Biogas plant		0,067	Number of items (biogas plant)		Kral et al. (2016)
Biogas production	Input	Electricity from grid (medium voltage)	Logarithmic normal distribution	498,00	MWh/a	1,00 (GSD)	Kral et al. (2016)
Biogas production	Input	Thermal energy	Logarithmic normal distribution	458,73	MWh/a	1,00 (GSD)	Kral et al. (2016)
Biogas production	Input	Substrate - Maize silage		10.585,00	t FM/a		own calculation, data based on Kral et al. (2016) & Fachagentur nachwachsende Rohstoffe (2016), further information in Appendix II
Biogas production	Input	Substrate - Pig slurry		4.443,48	t FM/a		own calculation, data based on Kral et al. (2016) & Fachagentur nachwachsende Rohstoffe (2016), further

							information in Appendix II
Biogas production	Output	Biogas	Triangular	min: 1.545.917,04 mod: 2.211.522,62 max: 2.440.323,811	Nm³/a		own calculation, data based on Kral et al. (2016) & Fachagentur nachwachsende Rohstoffe (2016), further information in Appendix II
Biogas production	Output	Methane from Fermenter leakages	Triangular	min: 1.070,77 mod: 1.552,59 max: 1.688,07	kg/a		own calculation, data based on Fachagentur nachwachsende Rohstoffe (2016) & Bachmaier (2012), further information in Appendix II
Biogas productin	Output	Fermentation Residue		12.287,89	t/a		own calculation, data based on Kral et al. (2016) & Fachagentur nachwachsende Rohstoffe (2016), further information in Appendix II

Pulp production	Input	Biogas	Triangular	min: 2,46 mean:2,60 max: 2,74	Nm^3		own calculation, further information in Appendix II
Pulp production	Output	sulfate pulp, from hardwood wood chips, bleached		1	kg		data based on Ecoinvent Association (2019)
Nano-cellulose production	Input	Water	Uniform	min: 5.000,00 max: 6.900,00	ml		Lab data (2019)
Nano-cellulose production	Input	Pulp		100,00	g		Lab data (2019)
Nano-cellulose production	Input	Electricity (medium voltage)	Uniform	min: 1,82 max: 2,14	kWh		Lab data (2019)
Nano-cellulose production	Output	Nano-Cellulose		83,70	g		Lab data (2019)

4.6.2. Statistical analysis

To test the robustness of input data with its probability distribution Monte Carlo simulations are conducted. In this method random values within the probability distribution for each input data are chosen and a high number of Monte Carlo runs are performed. Thereby, a probability distribution function for the output data is generated. In this master thesis 1.000 iterations are chosen, since a higher number of runs does not yield to more precise results (Kral et al., 2016).

The statistical significance between the two scenarios are tested with the Wilcoxon rank-sum test. It is a non-parametric test for two dependent samples, and it is chosen since the data is not normally distributed. With this test differences in the central location of distributions are checked (Janssen and Laatz, 2016). The significance level used is 0,05.

4.6.3. Sensitivity analysis

To estimate how changes in data and modelling assumptions affect the outcome of the LCA a certain number of sensitivity analysis are conducted. In this master thesis four different sensitivity analysis are examined. They are precisely described below. The results and their associated discussion can be found in chapter 5.2

(1) NFC production in the industrial scale:

The grinding step for which no proxy was found is upscaled in this sensitivity analysis. Since Turk et al. (2020) and Piccinno et al. (2018) stated that the environmental impacts could be reduced by a factor 3 to 6.5, the input data for the grinding step was decreased by the average of these factors which is 4,75. It must be taken into consideration that just the input material is included in this analysis, but no building or machine that would be necessary. Also, no probability distribution is used for the sensitivity analysis. The newly used input data is listed in Table 3.

Table 3: Life cycle inventory of the manure and the wood chips scenario for the sensitivity analysis (1) NFC production in the industrial scale

Scenario	Process	Input/ Output	Category	Amount	Unit	Reference
Wood chips	Nano-cellulose production	Input	Water	1.252,63	ml	Lab data (2019)
Wood chips	Nano-cellulose production	Input	Pulp	100,00	g	Lab data (2019)
Wood chips	Nano-cellulose production	Input	Electricity (medium voltage)	0,42	kWh	Lab data (2019)
Wood chips	Nano-cellulose production	Output	Nano-Cellulose	83,70	g	Lab data (2019)
Manure	Nano-cellulose production	Input	Water	84,21	ml	Lab data (2019)
Manure	Nano-cellulose production	Input	Pulp	50,00	g	Lab data (2019)
Manure	Nano-cellulose production	Input	Electricity (low voltage)	0,06	kWh	Lab data (2019)
Manure	Nano-cellulose production	Output	Nano-Cellulose	35,00	g	Lab data (2019)

(2) GWP credits:

In this sensitivity analysis it was examined how much environmental burdens expressed in kg CO_2 eq. can be avoided in the manure scenario when manure is used as biogas plant input material instead of being stored without a cover. Since there is no data for emissions of storing elephant manure, assumptions were taken from Amon et al. (2005). It is assumed that dairy cattle manure is stored over 180 days. Since emissions differ within the winter and summer period due to temperature changes, it is assumed that the manure is stored 90 days in the winter and 90 days in the summer period without a cover, respectively. The methane and nitrous oxide emissions were calculated using the CO_2 equivalent factors of 36 for methane and 298 for nitrous oxide which are assumptions from the IPCC (Goedkoop et al., 2013; Huijbregts et al., 2016). Referring to the functional unit of 1 kg nano-cellulose 20,93 kg of manure would be stored. Referring to the used biogas plant in the model which has a total input of 17.122 t manure per year, which is the amount that would otherwise have to be stored.

(3) Self-sufficient biogas plant:

In this sensitivity analysis the assumption is made that a co-generation plant (CHP) is installed after the biogas plant for both scenarios and the heat produced is used to cover the heat demand of the biogas plant. Therefore, the heat is not taken from the grid anymore as modelled in the manure and wood chips scenario, but the heat demand is fully covered by the waste heat of the CHP.

(4) Fertilizer application:

This sensitivity analysis does not refer to the manure scenario since there is no data yet how the nutrients in the fertilizer produced effect the soil. For the wood chips scenario, the fertilizer (fermentation residue of the biogas plant) application is assumed to be within the system boundaries. It was examined how much additional GWP expressed in kg CO_2 eq. occur due to the application of 17,13 kg of fertilizer which arise due to the production of 1 kg nano-cellulose. Further, it was also examined how much additional environmental burdens occur for 12.300 t of fertilizer which occur yearly in the whole biogas plant in the model.

5. Results

In this chapter the results of the life cycle assessment for both scenarios are shown and compared for the examined impact categories, respectively. The results are divided in two big sections:

- **Industrial part:** This part includes all processes that are upscaled to an industrial scale, including transportation, biogas production and pulp production.
- **Complete scenario:** This part includes the whole scenario, including both the industrial part and the nano-cellulose production.

The division of the two parts can be seen in Figure 12.

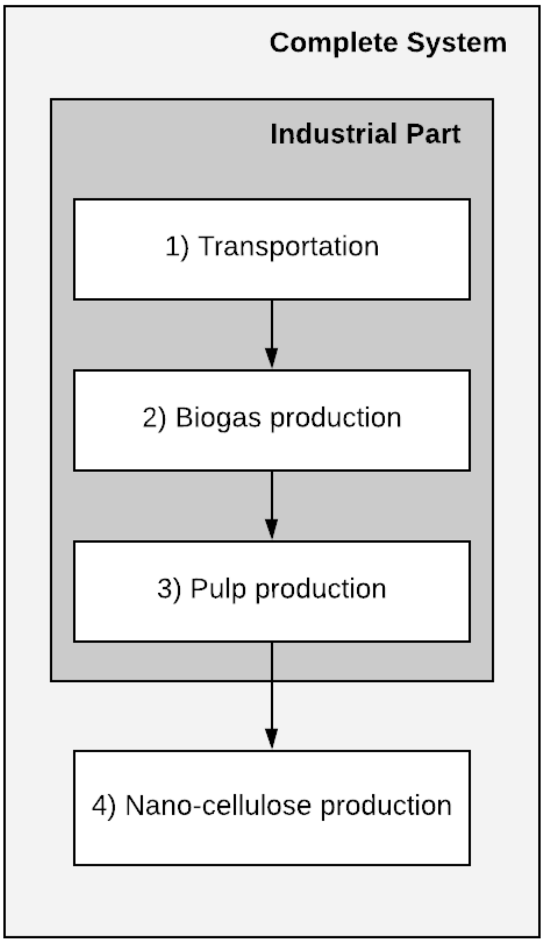

Figure 12: Division in the industrial part and the complete system

In Table 4 the results of the manure and the wood chips scenario for the complete scenario are shown. All result values are referring to the functional unit 1 kg nano-cellulose and are representing the median. The median divides the sample into two equal parts. Therefore, 50 % of the possible values are larger and 50 % of the possible values are smaller than the displayed value.

Table 4: Results of the manure and wood chips scenario for the complete scenario

Impact category	Amount per scenario		Unit
	Manure	Wood Chips	
Global Warming Potential	4,40902	9,74173	kg CO_2 eq./kg nano-cellulose
Fossil Resource Scarcity	1,11123	2,42366	kg oil eq./kg nano-cellulose
Freshwater Eutrophication Potential	0,00485	0,0111	kg P eq./kg nano-cellulose
Human Carcinogenic Toxicity Potential	0,45765	0,97921	kg 1,4-DCB/kg nano-cellulose
Human non-carcinogenic Toxicity Potential	5,92179	12,77087	kg 1,4-DCB/kg nano-cellulose
Terrestrial Acidification Potential	0,01364	0,07834	kg SO_2 eq./kg nano-cellulose
Terrestrial Ecotoxicity Potential	9,46131	17,04581	kg 1,4-DCB/kg nano-cellulose

In Table 5 the results of the manure and the wood chips scenario for the industrial part only are shown. All result values are again referring to the functional unit 1 kg nano-cellulose and are representing the median.

Table 5: Results of the manure and wood chips scenario for the industrial part

Impact category	Amount per scenario		Unit
	Manure	Wood Chips	
Global Warming Potential	1,42743	1,53554	kg CO_2 eq./kg nano-cellulose
Fossil Resource Scarcity	0,36766	0,37694	kg oil eq./kg nano-cellulose
Freshwater Eutrophication Potential	0,00091	0,00085	kg P eq./kg nano-cellulose
Human Carcinogenic Toxicity Potential	0,15545	0,13179	kg 1,4-DCB/kg nano-cellulose
Human non-carcinogenic Toxicity Potential	1,88885	2,08973	kg 1,4-DCB/kg nano-cellulose
Terrestrial Acidification Potential	0,00649	0,06151	kg SO_2 eq./kg nano-cellulose
Terrestrial Ecotoxicity Potential	6,1168	7,84058	kg 1,4-DCB/kg nano-cellulose

In Figure 13 the relative environmental impacts of all the examined impact categories for both the complete manure and wood chips scenario are shown. For every impact category the absolute result value from the two scenarios are compared and the higher number is set as 100 %. The lower number is shown as percentage share. With the relative environmental impact all impact categories can be shown in one figure, although the absolute values have different units. Therefore, this figure provides a good overview of what the relation of the results looks like.

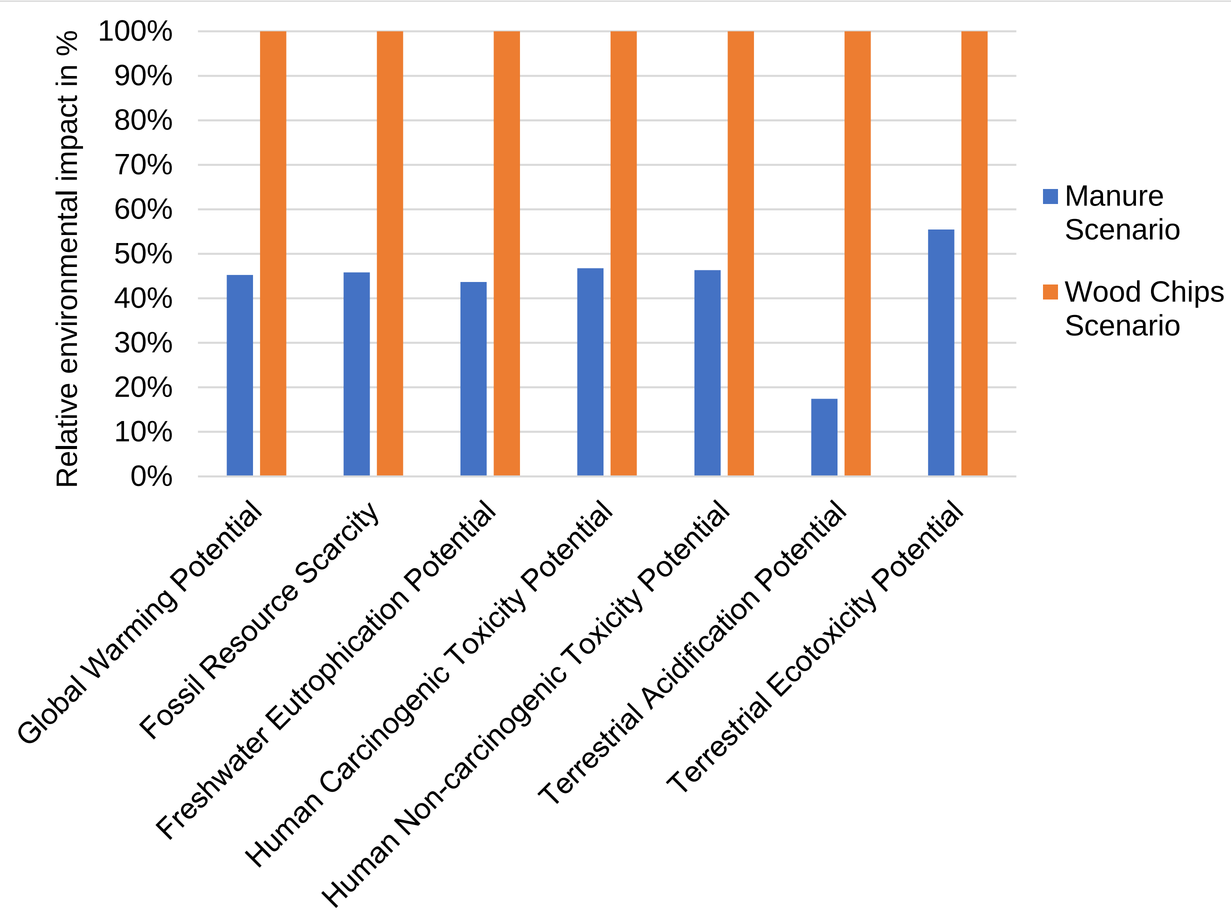

Figure 13: Relative environmental impacts of the examined impact categories for the complete process chains of both scenarios

As observable in Figure 13 the manure scenario has a lower relative environmental impact in all examined impact categories. While the relative impact of the manure scenario is between 43 % to 47 % compared to the wood chips scenario in most of the impact categories (GWP100, FRS, FEP, HCTP, HNCTP), the relative impact of the manure scenario in the terrestrial acidification potential is at a low level of 17 % compared to the wood chips scenario. In the impact category terrestrial ecotoxicity potential the manure scenario has the highest relative impact compared to the wood chips scenario with 55 %.

5.1. Contribution analysis of the manure scenario and the wood chips scenario

In the following figures the results are referring to the functional unit of the production of 1 kg of nano-cellulose. The result values again represent the median. The error bars show the 5 % to 95 % interpercentile range of the probability function. These values were calculated with 1.000 iterations of Monte-Carlo simulations. The ranges between the error bars cover 90 % of estimated results. The letters above the bars provide information about the statistical significance of the differences between the two scenarios. This information is based on a Wilcoxon rank-sum test. The specific results of this test are shown in Appendix III.

For every examined impact category there is a chapter with detailed contribution analysis of the results. The detailed contribution splits up the two big parts of the industrial part, the biogas and pulp production, into the following shares:

- **Biogas production:**
  - Biogas substrate production: Includes the transport of the elephant manure and the supply with water for dilution for the manure scenario and in the case of wood chips scenario the cultivation and transport of maize and the transport for pig slurry
  - Biogas plant construction: Construction material and the needed transport to the biogas plant site
  - Electricity and heat demand

- **Pulp production:**
  - Waste flows: Includes the waste management of green liquor dregs, waste wood, limestone residue, sludge from the pulp production, inert and municipal waste and waste mineral oil
  - Miscellaneous part: Construction of the pulp factory, transports by lorry, train and ship and for the wood chips scenario also the cultivation and transport of the pulpwood
  - Chemicals: Supply of all the needed pulping chemicals including the transport
  - Energy carrier: Includes the use of heavy and light fuel oil, natural gas and electricity

In the following figures which only display the results of the industrial part of both scenarios the contributions from the biogas production are displayed in reddish shades, contributions from the pulp production are displayed in blueish shades.

5.1.1. Climate change (GWP100)

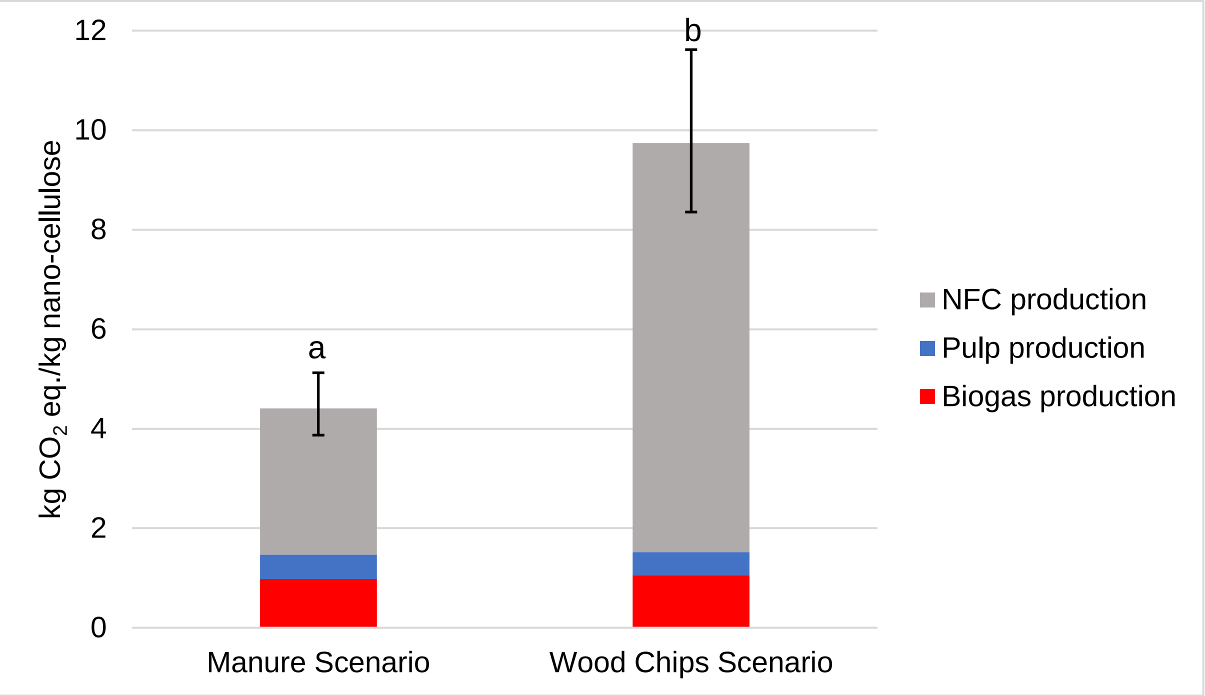

Figure 14: Contribution analysis of GWP100 of the complete manure and wood chips scenario (n=1.000)

In Figure 14 the absolute global warming potential of the complete manure and wood chips scenario is shown, which is 4,41 kg CO_2 eq./kg nano-cellulose for the manure scenario and more than double than that, exactly 9,74 kg CO_2 eq./kg nano-cellulose for the wood chips scenario. The major part of the contribution for both scenarios is coming from the nano-cellulose production which is the last step in the fabrication route. For the manure scenario this step contributes 66,64 % (2,93 kg CO_2 eq./kg nano-cellulose) to the GWP and for the wood chips scenario 84,42 % (8,22 kg CO_2 eq./kg nano-cellulose). The electricity needed in the NFC production step (displayed in grey in Figure 14) contributes for both scenarios 99 % to this last fabrication step. The electricity mix for Austria from the Ecoinvent database is used and the highest share of this part is coming from electricity imports from Germany (36,35 %) and the Czech Republic (33,03 %). The pulp production has an impact of

0,49 kg CO_2 eq./kg nano-cellulose (11,11 %) for the manure scenario and 0,47 kg CO_2 eq./kg nano-cellulose (4,80 %) for the wood chips scenario. The biogas production has an impact of 0,98 kg CO_2 eq./kg nano-cellulose (22,25 %) for the manure scenario and 1,05 kg CO_2 eq./kg nano-cellulose (10,78 %) for the wood chips scenario.

Since the contribution of the GWP of pulp and biogas production is coming from different sources, a detailed contribution is shown in Figure 15. The following percentage values are referring to the median values of the results of the industrial part of both scenarios (see Table 5).

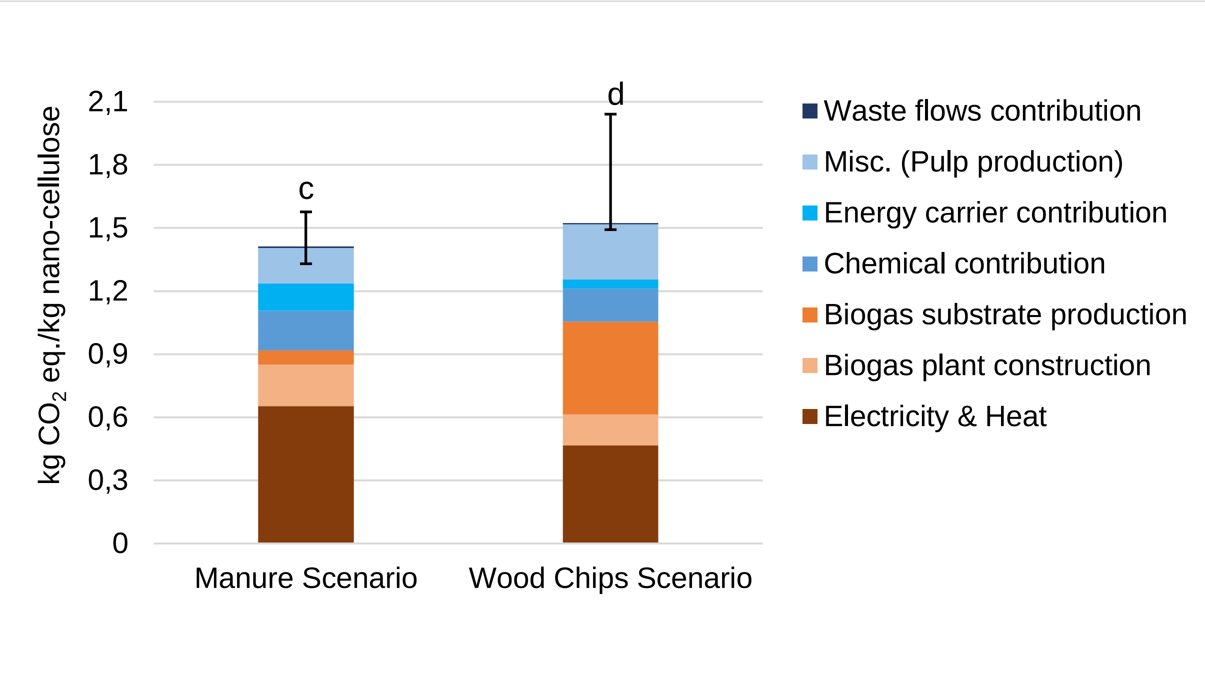

Figure 15: Detailed contribution analysis of GWP100 of the industrial part (biogas and pulp production) of the manure and wood chips scenario (n=1.000); blueish shades = impacts related to pulp production, reddish shades = impacts related to biogas production

The highest share of the contribution to GWP of the manure scenario is coming from the electricity and heat demand (0,65 kg CO_2 eq./kg nano-cellulose), each contributing 50 %, respectively. The electricity and heat demand (0,46 kg CO_2 eq./kg nano-cellulose) and the substrate production (0,44 kg CO_2 eq./kg nano-cellulose) have the highest share in the wood chips scenario, the latter due to the production of maize silage as input material for the biogas plant and the therefore needed use of heavy machinery and the fertilisation with liquid fermentation residue. The biogas plants consist of the same construction materials, but due to the worse yield by producing nano-cellulose from manure more pulp and therefore a higher share of the biogas plant is needed. The biggest impacts have the construction materials concrete and mastic asphalt for both scenarios.

The miscellaneous share from the pulp production includes for both scenarios transports by lorry, ship and train, the construction of the pulp factory and for the wood chips scenario also the production of the pulp wood. Taken this into account, the higher contribution of the miscellaneous part in the wood chips scenario is explained (0,26 kg CO_2 eq./kg nano-cellulose for the wood chips and 0,16 kg CO_2 eq./kg nano-cellulose for the manure scenario), since the production of pulpwood has the highest share of 34,51 %. The second and third biggest contribution for the wood chips scenario and the highest and second highest share for the manure scenario is originating from transports of pulp by train and by lorry.

The contribution of different chemicals is dominated with 41,55 % for the manure scenario and 54,33 % for the wood chips scenario by the impacts of two chemicals, sodium chlorate and sodium hydroxide. Further, in the manure scenario oxygen contributes 25,69 % to the share, which means that three chemicals are responsible for just less than three-quarters of the contributions from chemicals. The situation appears similar for the wood chips scenario; however, sulfuric acid contributes 21,29 % to the share which leads to a contribution of 75,62 % from just these three chemicals. The absolute higher values in the chemical and energy carrier contribution in the manure scenario are due to the worse yield by producing nano-cellulose from manure than from wood chips. Therefore, more pulp is needed which leads to a higher absolute contribution from these two parts.

The highest contribution from the energy carriers (0,13 kg CO_2 eq./kg nano-cellulose for the manure and 0,04 kg CO_2 eq./kg nano-cellulose for the wood chip scenario) is originating from high voltage electricity for the manure scenario and from natural gas for the wood chips scenario.

As can be seen from Figure 15 the waste flows contributions have a subordinate status in this impact category. In general, the contribution of the waste flows is the same for both scenarios (0,01 kg CO_2 eq./kg nano-cellulose).

5.1.2. Fossil resource scarcity (FRS)

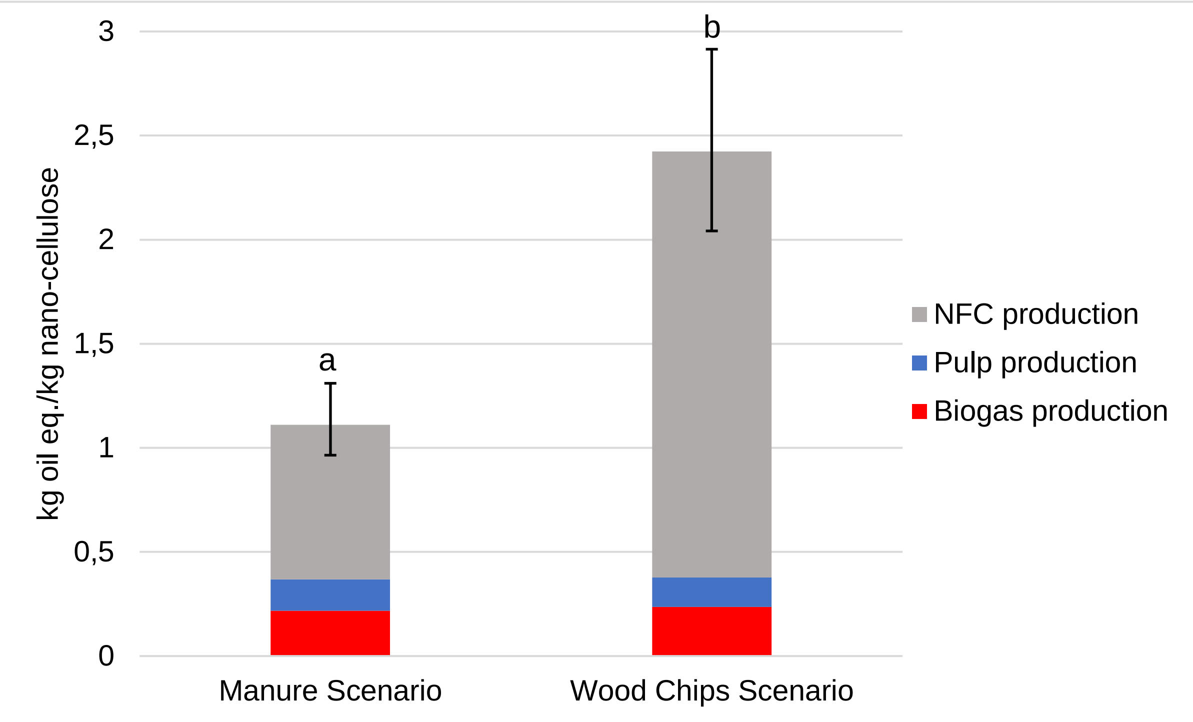

Figure 16: Contribution analysis to fossil resource scarcity of the complete manure and wood chips scenario (n=1.000)

In Figure 16 the absolute values of the fossil resource scarcity impact category of the complete manure and wood chips scenario are shown. Compared with the FRS of the wood chips scenario the manure scenario has around half of the impact (2,42 kg oil eq./kg nano-cellulose compared to 1,11 kg oil eq./kg nano-cellulose). The major part of the contribution for both scenarios is again coming from the nano-cellulose production. For the manure scenario this step contributes 66,85 % (0,734kg oil eq./kg nano-cellulose) to the FRS and for the wood chips scenario 84,44 % (2,05 kg oil eq./kg nano-cellulose). While the electricity needed for the NFC production step (displayed in grey in Figure 16) is the main contributor (99 %) for both scenarios, the needed water is negligible. The pulp production has an impact of 0,15 kg oil eq./kg nano-cellulose for the manure scenario and 0,14 kg oil eq./kg nano-cellulose for the wood chips scenario. The biogas production has an impact of 0,22 kg oil eq./kg nano-cellulose for the manure scenario and a slightly higher impact of 0,24 kg oil eq./kg nano-cellulose for the wood chips scenario.

In Figure 17 a detailed analysis of the biogas and pulp production for both scenarios is shown. The following percentage values are referring to the median values of the results of the industrial part of both scenarios (see Table 5).

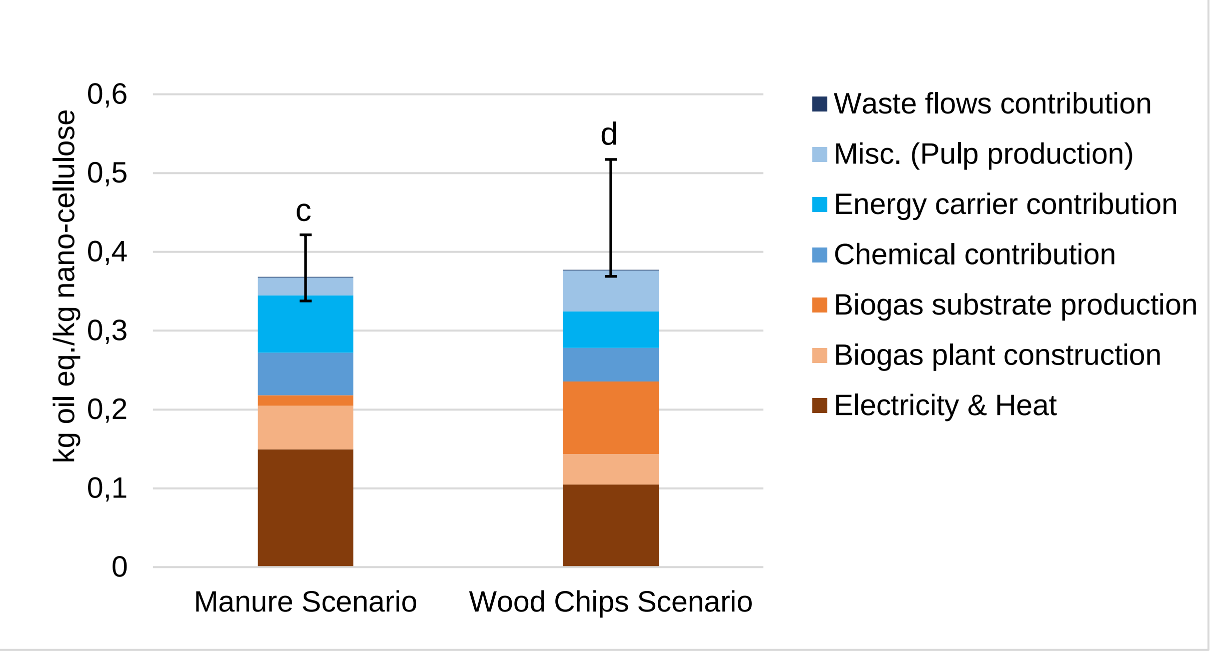

Figure 17: Detailed contribution analysis to fossil resource scarcity of the industrial part of the manure and wood chips scenario (n=1.000); blueish shades = impacts related to pulp production, reddish shades = impacts related to biogas production

The highest share of the contribution is coming again for both scenarios from the electricity and heat demand with 40,67 % for the manure scenario (0,15 kg oil eq./kg nano-cellulose) and with 27,76 % for the wood chips scenario (0,10 kg oil eq./kg nano-cellulose). The second biggest share for the wood chips scenario is the substrate production with 24,63 % (0,09 kg oil eq./kg nano-cellulose) especially due to the high impact of the use of diesel for heavy machinery and fertilisation with liquid fermentation residue. The biogas plant construction has an impact of 0,06 kg oil eq./kg nano-cellulose for the manure scenario (15,02 %) and an impact of 0,04 kg oil eq./kg nano-cellulose for the wood chips scenario (10,25 %) with the biggest impacts contributed by concrete and mastic asphalt for both scenarios.

The miscellaneous part contributes 0,05 kg oil eq./kg nano-cellulose to the wood chips and 0,02 kg oil eq./kg nano-cellulose to the manure scenario. The main contributors of the wood chips scenario are the pulpwood production (57,59 %), transports of pulp by lorry and the pulp factory construction. In the manure scenario the highest and second highest share is originating from transports of pulp by train and by lorry.

The contribution of different chemicals (0,05 kg oil eq./kg nano-cellulose for the manure and 0,04 kg oil eq./kg nano-cellulose for the wood chips scenario) is dominated with 47,50 % for the manure scenario by sodium chlorate and 51,71 % for the wood chips scenario by sodium hydroxide.

The absolute higher values in the chemical and energy carrier contribution in the manure scenario are due to the worse yield by producing nano-cellulose from manure than from wood chips. Therefore, more pulp is needed which leads to a higher absolute contribution from these two parts.

The highest contribution from the energy carriers (0,07 kg oil eq./kg nano-cellulose for the manure and 0,04 kg oil eq./kg nano-cellulose for the wood chips scenario) is originating from natural gas for the manure scenario and from heavy fuel oil for the wood chips scenario.

As can be seen from Figure 17 the waste flows contribute less than 0,01 kg oil eq./kg nano-cellulose for both scenarios and are therefore negligible.

5.1.3. Freshwater eutrophication potential (FEP)

Attention should be drawn to the fact that the data from the Ecoinvent database has such a high dispersion that the error bars showing the 5 % to 95 % interpercentile range would make the bar graphs small and therefore unreadable. The values of the 5 % and 95 % percentile for both scenarios are therefore displayed in Table 6.

Table 6: 5 % to 95 % interpercentile range for the freshwater eutrophication potential for the complete manure and wood chips scenario

	5 % percentile	95 % percentile	Unit
Manure Scenario	0,00248	0,01350	kg P eq./kg nano-cellulose
Wood Chips Scenario	0,00495	0,02921	kg P eq./kg nano-cellulose

In Figure 18 the absolute values of the fossil resource scarcity impact category of the complete manure and wood chips scenario are shown.

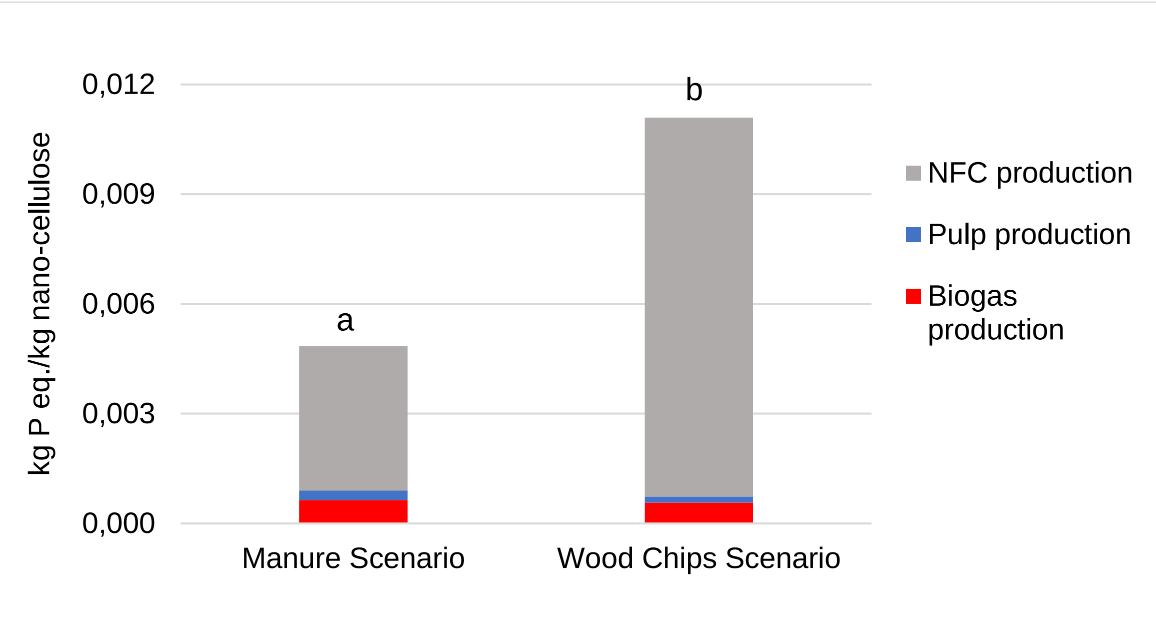

Figure 18: Contribution analysis of the freshwater eutrophication potential of the complete manure and wood chips scenario (n=1.000)

Compared to the manure scenario with an impact of 0,0049 kg P eq./kg nano-cellulose the wood chips scenario has an impact more than double than that with 0,0111 kg P eq./kg nano-cellulose. For the NFC production step (81,49 % of manure scenario and 93,38 % of wood chips scenario) only the needed electricity matters with a contribution to this step of 99 % for both scenarios and the highest share coming from high voltage imports from Germany and the Czech Republic.

The pulp and biogas production have a comparatively low impact to FEP in both scenarios. The pulp production has an impact of 0,0003 kg P eq./kg nano-cellulose

(5,29 %) for the manure scenario and 0,0002 kg P eq./kg nano-cellulose (1,48 %) for the wood chips scenario. The biogas production has an impact of 0,0006 kg P eq./kg nano-cellulose (13,22 %) for the manure scenario and 0,0006 kg P eq./kg nano-cellulose (5,14 %) for the wood chips scenario.

In Figure 19 a detailed analysis of the biogas and pulp production for both scenarios is shown. The following percentage values are referring to the median values of the results of the industrial part of both scenarios (see Table 5).

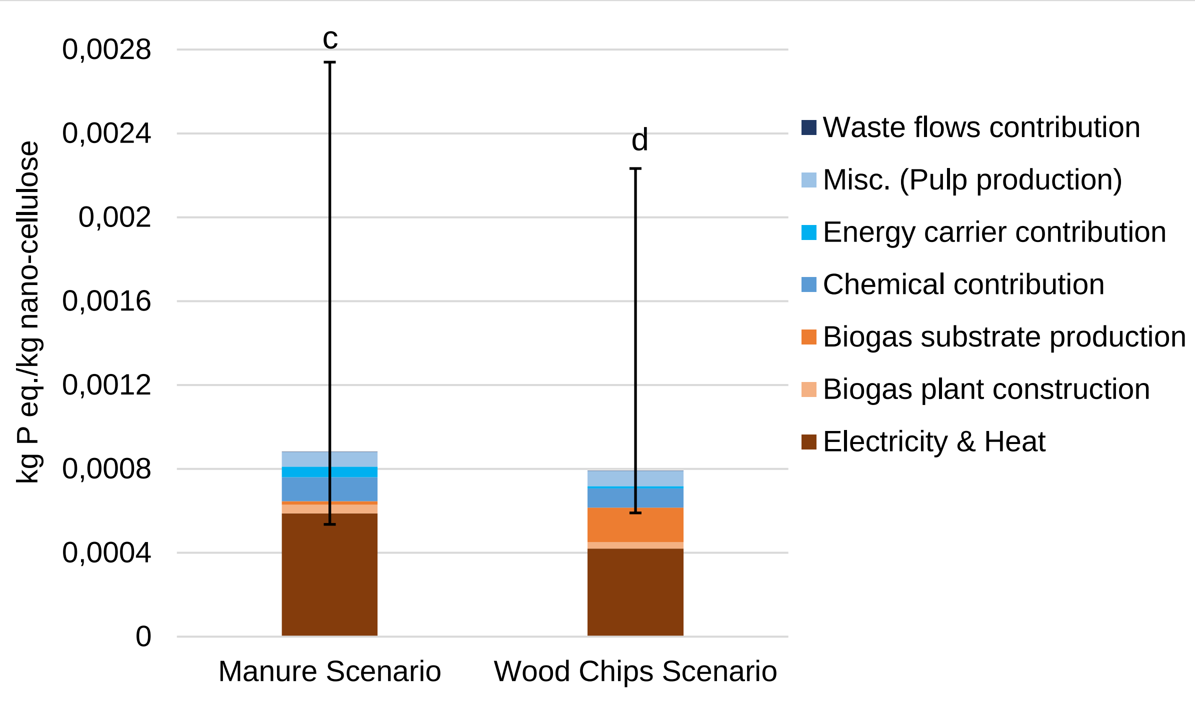

Figure 19: Detailed contribution analysis of the freshwater eutrophication potential of the industrial part of the manure and wood chips scenario (n=1.000); blueish shades = impacts related to pulp production, reddish shades = impacts related to biogas production

In the manure scenario the highest share of the contribution is coming from the electricity and heat demand with 64,70 % (0,0006 kg P eq./kg nano-cellulose). The main contributors to the wood chips scenario are the electricity and heat demand (49,54 %; 0,0004 kg P eq./kg nano-cellulose) followed by the substrate production (19,40 %; 0,0002 kg P eq./kg nano-cellulose). For the latter the highest impact coming from phosphorus emissions to water due to the maize silage production. The substrate production is negligible in the manure scenario (1,82 %) since all environmental impacts of elephant manure are allocated to keeping elephants and therefore, no upstream environmental burden is considered which leads to such a big difference in the two scenarios. The biogas plant construction contributes 4,56 % to the manure scenario and 10,25 % to the wood chips scenario, respectively. The biggest impacts have the construction materials mastic asphalt and reinforcing steel for both scenarios.

The miscellaneous share including transports, the construction of the pulp factory and for the wood chips scenario also the production of the pulp wood counts less than 0,0001 kg P eq./kg nano-cellulose for both scenarios.

Sodium chlorate has the highest impact in the chemical contribution with 42,70 % for the manure and 40,28 % for the wood chips scenario, respectively. In addition, sodium hydroxide and oxygen contribute together another 40 % to the chemical contribution in both scenarios.

The absolute higher values in the chemical and energy carrier contribution in the manure scenario are due to the worse yield by producing nano-cellulose from manure than from wood chips. Therefore, more pulp is needed which leads to a higher absolute contribution from these two parts.

The waste flows contribution is below 1 % for both scenarios and therefore negligible.

5.1.4. Human carcinogenic toxicity potential (HCTP)

As the Ecoinvent database has such a high dispersion that the error bars showing the 5 % to 95 % interpercentile range would make the bar graphs small and therefore unreadable. The values of the 5 % and 95 % percentile for both complete scenarios are therefore displayed in Table 7.

Table 7: 5 % to 95 % interpercentile range for the human carcinogenic toxicity potential for the complete manure and wood chips scenario

	5 % percentile	**95 % percentile**	**Unit**
Manure Scenario	0,29	7,02	kg 1,4-DCB/kg nano-cellulose
Wood Chips Scenario	0,52	17,31	kg 1,4-DCB/kg nano-cellulose

In Figure 20 the absolute values of the human carcinogenic toxicity potential impact category of the complete manure and wood chips scenario are shown.

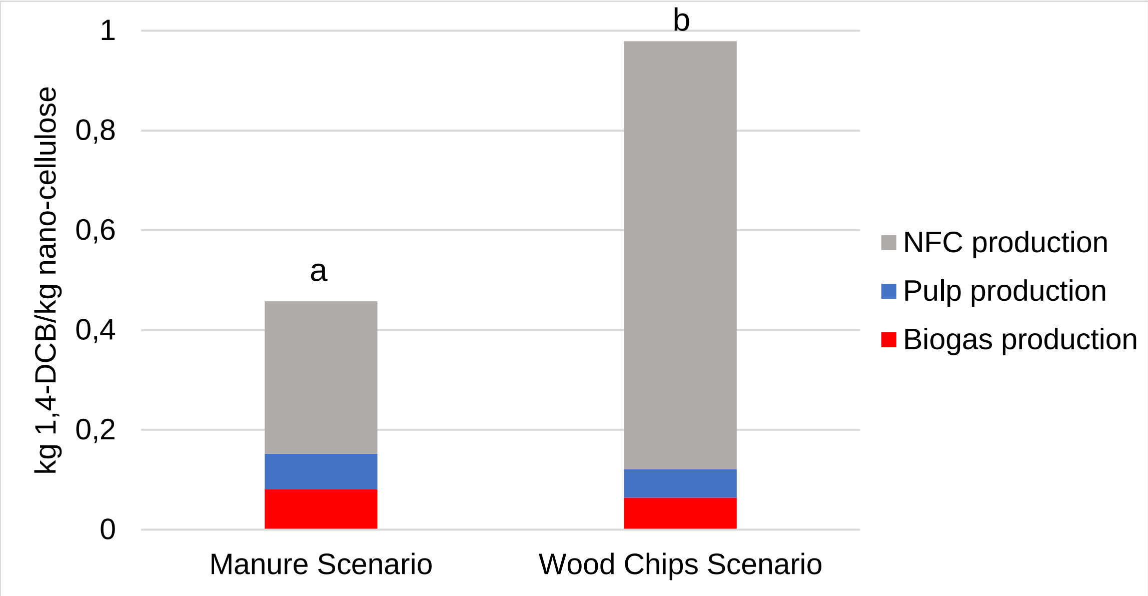

Figure 20: Contribution analysis of the human carcinogenic toxicity potential of the complete manure and wood chips scenario (n=1.000)

The manure scenario has around half the impact of the wood chips scenario (0,46 kg 1,4-DCB/kg nano-cellulose in contrast to 0,98 kg 1,4-DCB/kg nano-cellulose). For both scenarios the NFC production and the therefore needed energy demand are the main contributor to HCTP (66,76 % to the manure and 87,62 % to the wood chips scenario, respectively). The remaining impact to the manure scenario is split between the pulp production (15,61 %, 0,07 kg 1,4-DCB/kg nano-cellulose) and the biogas production (17,63 %; 0,08 kg 1,4-DCB/kg nano-cellulose). The pulp and biogas production show lower relative impact in the wood chips scenario (5,82 % for the pulp production and 6,57 % for the biogas production, respectively).

As the Ecoinvent database has such a high dispersion that the error bars showing the 5 % to 95 % interpercentile range would make the bar graphs small and therefore unreadable, the values of the 5 % and 95 % percentile for the industrial parts of both scenarios are therefore displayed in Table 8.

Table 8: 5 % to 95 % interpercentile range for the human carcinogenic toxicity potential for the industrial part of the manure and wood chips scenario

	5 % percentile	95 % percentile	Unit
Manure Scenario	0,14	1,62	kg 1,4-DCB/kg nano-cellulose
Wood Chips Scenario	0,13	1,25	kg 1,4-DCB/kg nano-cellulose

In Figure 21 a detailed analysis of the industrial part for both scenarios is shown. The following percentage values are referring to the median values of the results of the industrial part of both scenarios (see Table 5).

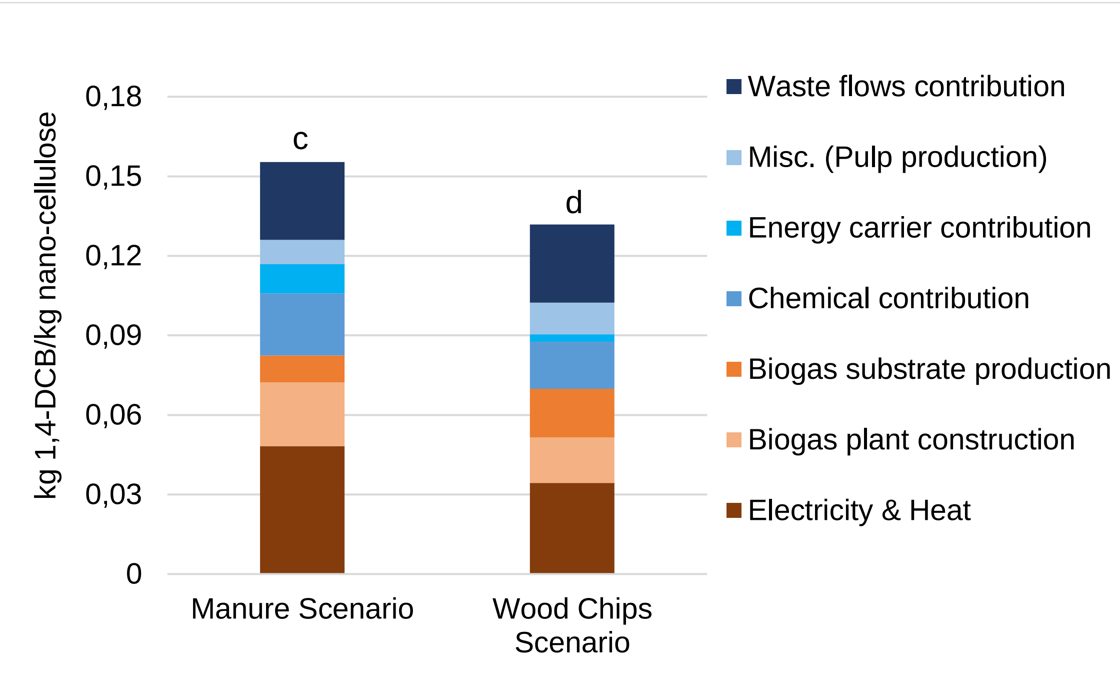

Figure 21: Detailed contribution analysis of the human carcinogenic toxicity potential of the industrial part of the manure and wood chips scenario (n=1.000); blueish shades = impacts related to pulp production, reddish shades = impacts related to biogas production

The highest share of the contribution to the biogas production in the manure scenario is coming from the electricity and heat demand (31,01 %) followed by the biogas plant construction (15,49 %). The biggest impacts have the construction materials reinforcing steel and concrete for both scenarios. The substrate production plays a subordinate role with a contribution of 6,52 %. In the wood chips scenario, the main contributor is also the electricity and heat demand (26,06 %) followed by the substrate production (13,96 %) and the biogas plant construction with 13,96 %. The difference in contributions to the overall biogas production of the two scenarios occurs since the production of maize silage is demanding the use of heavy machinery and fertilisation which both have a high environmental impact.

The waste flows contributions are essential to the HCTP with a total share of 18,95 % (0,03 kg 1,4-DCB/kg nano-cellulose) for the manure scenario and with a share of 22,35 % (0,03 kg 1,4-DCB/kg nano-cellulose) for the wood chips scenario which makes it the second biggest share in the industrial part for both scenarios. The main contributor is the waste disposal of green liquor dregs, related to chromium emissions to ground and surface water.

The contribution from energy carriers is around three times higher in the manure scenario (0,01 kg 1,4-DCB/kg nano-cellulose) than in the wood chips scenario (0,003 kg 1,4-DCB/kg nano-cellulose). The highest share originates from high voltage electricity for both scenarios. The higher value in the energy carrier contribution in the manure scenario is due to the worse yield by producing nano-cellulose from manure than from wood chips. Therefore, more pulp is needed which leads to a higher absolute contribution.

The pulp factory construction is the main contributor to the miscellaneous share from the pulp production in both scenarios (in total around 0,01 kg 1,4-DCB/kg nano-cellulose for both scenarios, respectively). The production of pulpwood has a share of 33,47 %.

An essential share of the total contribution of pulping chemical production (in total around 0,02 kg 1,4-DCB/kg nano-cellulose for both scenarios, respectively) is originating from the impact of sodium chlorate in both scenarios with around 51 %.

5.1.5. Human non-carcinogenic toxicity potential (HNCTP)

As the data from the Ecoinvent database has such a high dispersion that the error bars showing the 5 % to 95 % interpercentile range would make the bar graphs small and therefore unreadable, the values of the 5 % and 95 % percentile for both complete scenarios are therefore displayed in Table 9.

Table 9: 5 % to 95 % interpercentile range for the human non-carcinogenic toxicity potential for the complete manure and wood chips scenario

	5 % percentile	95 % percentile	Unit
Manure Scenario	4,12	30,22	kg 1,4-DCB/kg nano-cellulose
Wood Chips Scenario	8,25	66,96	kg 1,4-DCB/kg nano-cellulose

In Figure 22 the absolute values of the human non-carcinogenic toxicity potential impact category of the complete manure and wood chips scenario are shown.

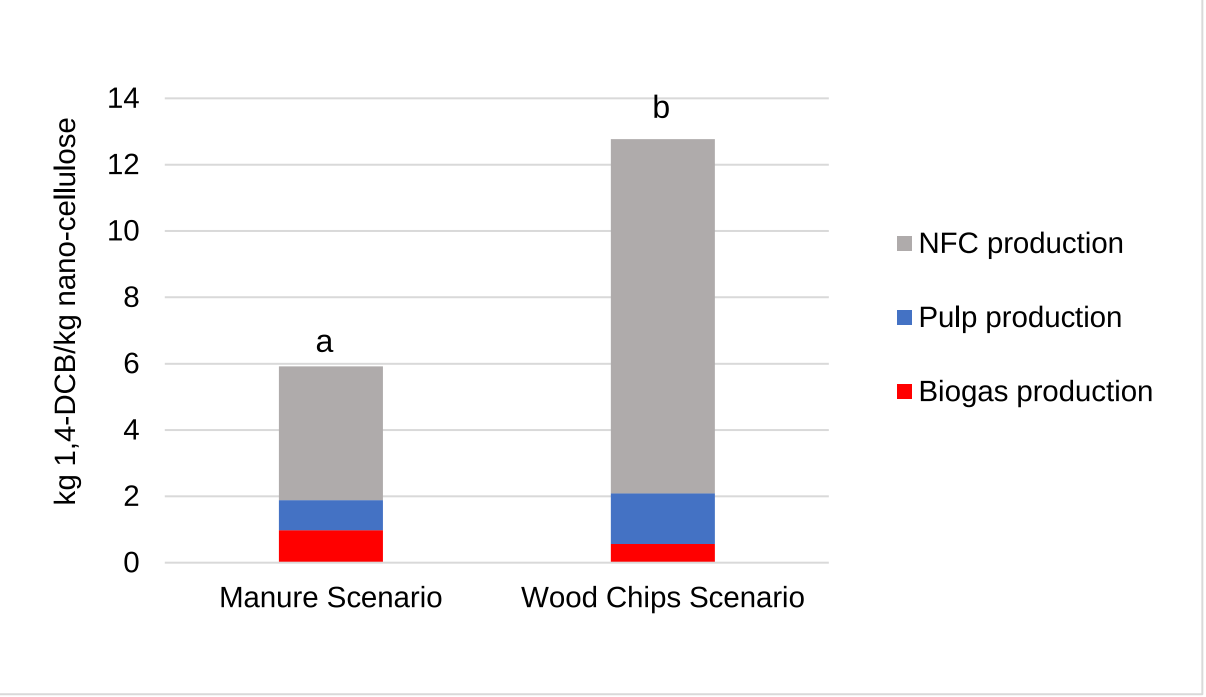

Figure 22: Contribution analysis of the human non-carcinogenic toxicity potential of the complete manure and wood chips scenario (n=1.000)

The manure scenario has a total impact of 5,92 kg 1,4-DCB/kg nano-cellulose with 4,03 kg 1,4-DCB/kg nano-cellulose (68,10 %) originating from the NFC production, while the wood chips scenario has a total impact of 12,77 kg 1,4-DCB/kg nano-cellulose with 10,68 kg 1,4-DCB/kg nano-cellulose (83,64 %) originating from the NFC production. In both scenarios the main contributor to the NFC step is the needed electricity contributing 99 % with the highest shares originating from high voltage imports from Germany and the Czech Republic. While the pulp production plays a subordinate role in the wood chips scenario with an impact of 0,56 kg 1,4-DCB/kg nano-cellulose (4,41 %), in the manure scenario it has an impact of 0,91 kg 1,4-DCB/kg nano-cellulose (15,33 %). More similar results show the contributions of the biogas production with an impact of 0,98 kg 1,4-DCB/kg nano-cellulose (16,57 %) for the manure scenario and 1,52 kg 1,4-DCB/kg nano-cellulose (11,95 %) for the wood chips scenario.

Due to the fact that the data from the Ecoinvent database has such a high dispersion that the error bars showing the 5 % and 95 % percentile would make the bar graphs small and therefore unreadable, the values of the 5 % and 95 % percentile for the industrial parts of both scenarios are therefore displayed in Table 10.

Table 10: 5 % and 95 % percentile for the human non-carcinogenic toxicity potential for the industrial part of the manure and wood chips scenario

	5 % percentile	**95 % percentile**	**Unit**
Manure Scenario	1,77	8,39	kg 1,4-DCB/kg nano-cellulose
Wood Chips Scenario	0,50	8,51	kg 1,4-DCB/kg nano-cellulose

In Figure 23 a detailed analysis of the industrial part for both scenarios is shown. The following percentage values are referring to the median values of the results of the industrial part of both scenarios (see Table 5).

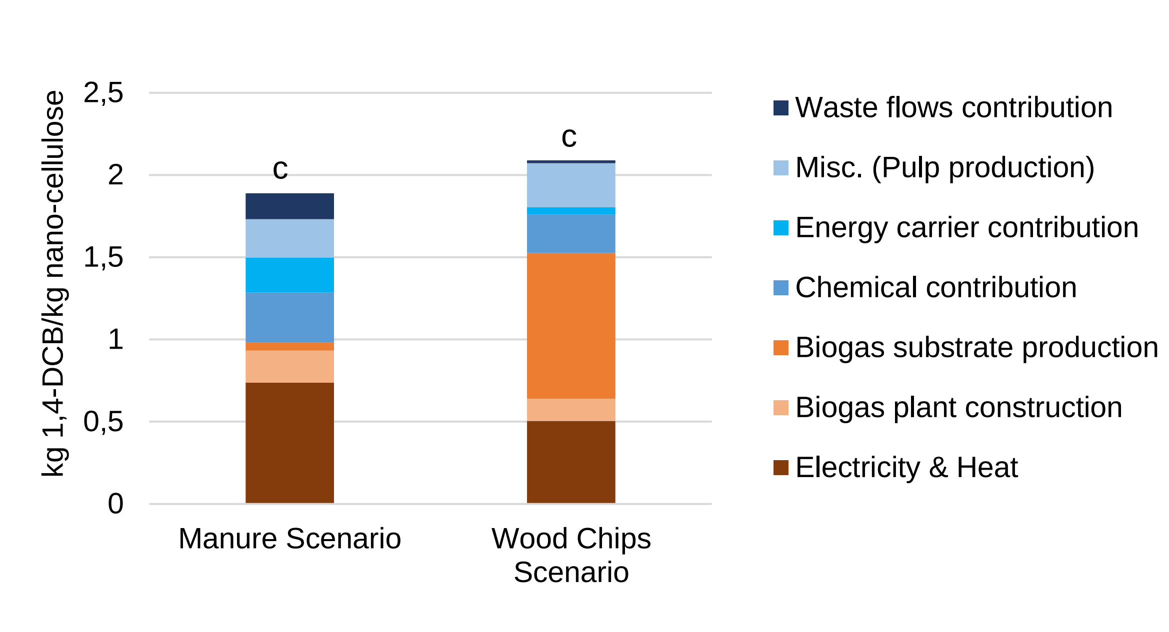

Figure 23: Detailed contribution analysis of the human non-carcinogenic toxicity potential of the industrial part of the manure and wood chips scenario (n=1.000); blueish shades = impacts related to pulp production, reddish shades = impacts related to biogas production

The substrate production has the highest impact in the wood chips scenario with 42,50 % (0,89 kg 1,4-DCB/kg nano-cellulose), while for the manure scenario the substrate production is negligible with a contribution of 2,62 % (0,05 kg 1,4-DCB/kg nano-cellulose). This big difference occurs since the production of maize silage, especially the maize seed production, the use of heavy machinery and the fertilisation with liquid fermentation residue have high contributions to HNCTP. Especially the emission of zinc to the ground water and soil has a high impact.

The electricity and heat demand has the highest share of the contribution for the manure scenario with 39,07 % (0,74 kg 1,4-DCB/kg nano-cellulose) and the second highest contribution for the wood chips scenario with 24,19 % (0,51 kg 1,4-DCB/kg nano-cellulose).

The biogas plant construction has an impact of 0,19 kg 1,4-DCB/kg nano-cellulose for the manure scenario (10,24 %) compared to an impact of 0,13 kg 1,4-DCB/kg nano-cellulose for the wood chips scenario (6,34 %). The biggest impacts have the construction materials concrete and mastic asphalt for both scenarios.

While the pulp factory construction has the highest contribution to the miscellaneous share from the pulp production for both scenarios (0,23 kg 1,4-DCB/kg nano-cellulose for the manure and 0,27 kg 1,4-DCB/kg nano-cellulose for the wood chips scenario), the impact originating from pulping chemical production is dominated by sodium chlorate with 35,18 % for the manure scenario and 33,64 % for the wood chips scenario.

The roughly four times higher impact of the contribution from energy carriers in the manure scenario (0,12 kg 1,4-DCB/kg nano-cellulose in contrast to 0,03 kg 1,4-DCB/kg nano-cellulose for the wood chips scenario) is due to the worse yield by producing nano-cellulose from manure than from wood chips. Therefore, more pulp is needed which leads to a higher absolute contribution. The same applies to the impact from pulping chemical production.

In this impact category the waste flows contribution for the manure scenario are essential with a total share of 8,30 % (0,16 kg 1,4-DCB/kg nano-cellulose). The highest contribution originates from the disposal of wood ash mixture related to emissions of zinc and cadmium to agricultural soil (88,24 %). In the wood chips scenario, the waste flows contribution is negligible.

5.1.6. Terrestrial acidification potential (TAP)

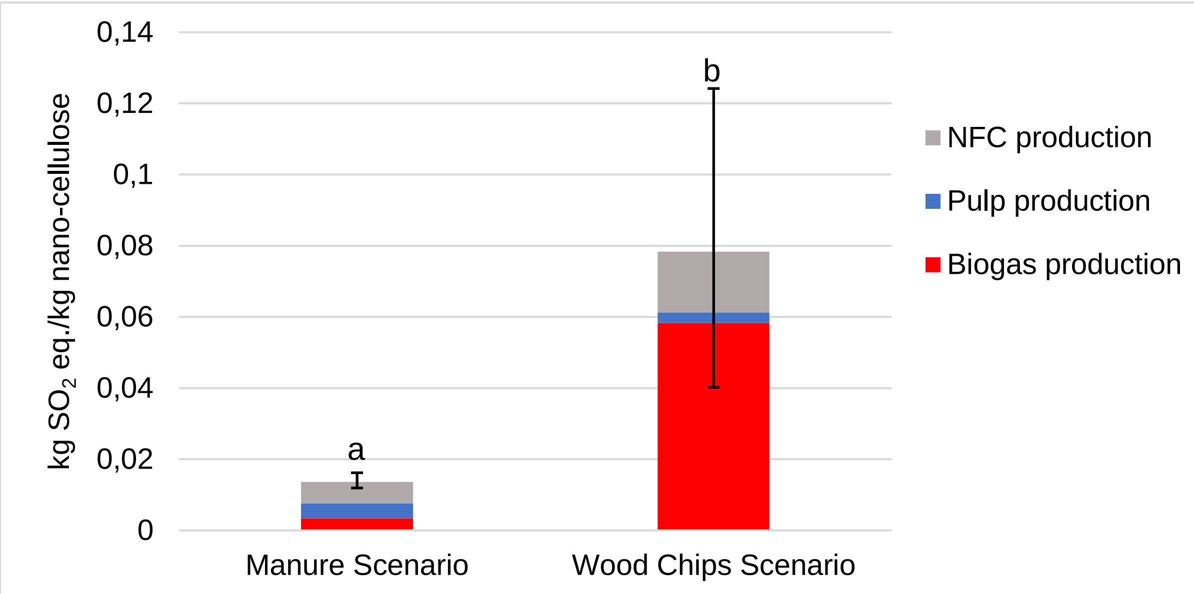

Figure 24: Contribution analysis of the terrestrial acidification potential of the complete manure and wood chips scenario (n=1.000)

In Figure 24 the absolute values of the terrestrial acidification potential impact category of the complete manure and wood chips scenario are shown, which is 0,01 kg SO_2 eq./kg nano-cellulose for the manure scenario and seven times higher than that 0,07 kg SO_2 eq./kg nano-cellulose for the wood chips scenario. Around half of the contribution for the manure scenario is coming from the NFC production. For the manure scenario this step contributes 44,17 % (0,01 kg SO_2 eq./kg nano-cellulose) to TAP and for the wood chips scenario 21,79 % (0,02 kg SO_2 eq./kg nano-cellulose) which makes it the second biggest share. The biggest impact is originating from the biogas production for the wood chips scenario with 74,46 % (0,06 kg SO_2 eq./kg nano-cellulose) while the pulp production plays a minor role with a contribution of 3,75 %.

The biogas production and the pulp production play a similar role in the manure scenario with 24,60 % and 31,23 %, respectively.

In Figure 25 a detailed analysis of the biogas and pulp production for both scenarios is shown. The following percentage values are referring to the median values of the results of the industrial part of both scenarios (see Table 5).

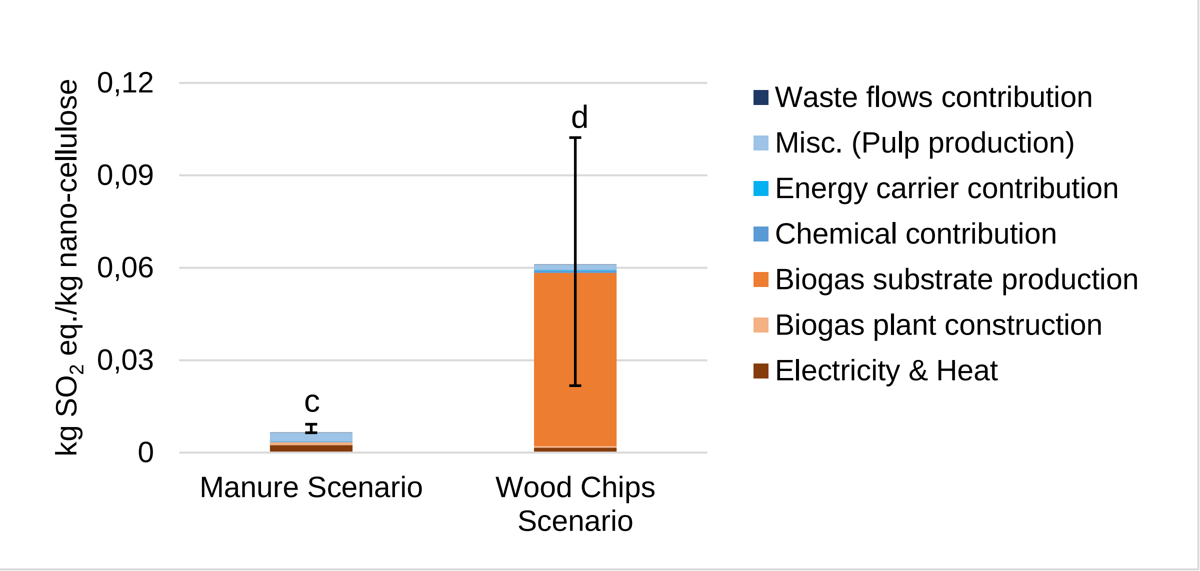

Figure 25: Detailed contribution analysis of the terrestrial acidification potential of the industrial part of the manure and wood chips scenario (n=1.000); blueish shades = impacts related to pulp production, reddish shades = impacts related to biogas production

The production of biogas substrate production has the largest contribution in the wood chips scenario with 91,42 % (0,05 kg SO_2 eq./kg nano-cellulose). The other contributions play a minor role and are originating from the miscellaneous part (2,90 %), the energy and heat demand of the biogas plant (2,64 %) and from the chemical production (1,22 %). The contributions of the biogas plant construction (0,78 %), from the energy carriers (0,30 %) and from the waste flows (0,02 %) are negligible. The substrate production has such a high impact due to the fertilisation with liquid fermentation residue by a vacuum tanker and the therefore occurring ammonia emissions to the air.

The highest contributions in the manure scenario originate from the miscellaneous part of the pulp production with 44,36 % (0,0029 kg SO_2 eq./kg nano-cellulose), from the electricity and heat demand of the biogas plant with 38,08 % (0,0025 kg SO_2 eq./kg nano-cellulose) and from the biogas plant construction with 11,49 % (0,0001 kg SO_2 eq./kg nano-cellulose). The substrate production (2,19 %) and the waste flows contribution (0,78 %) are negligible.

5.1.7. Terrestrial ecotoxicity potential (TEP)

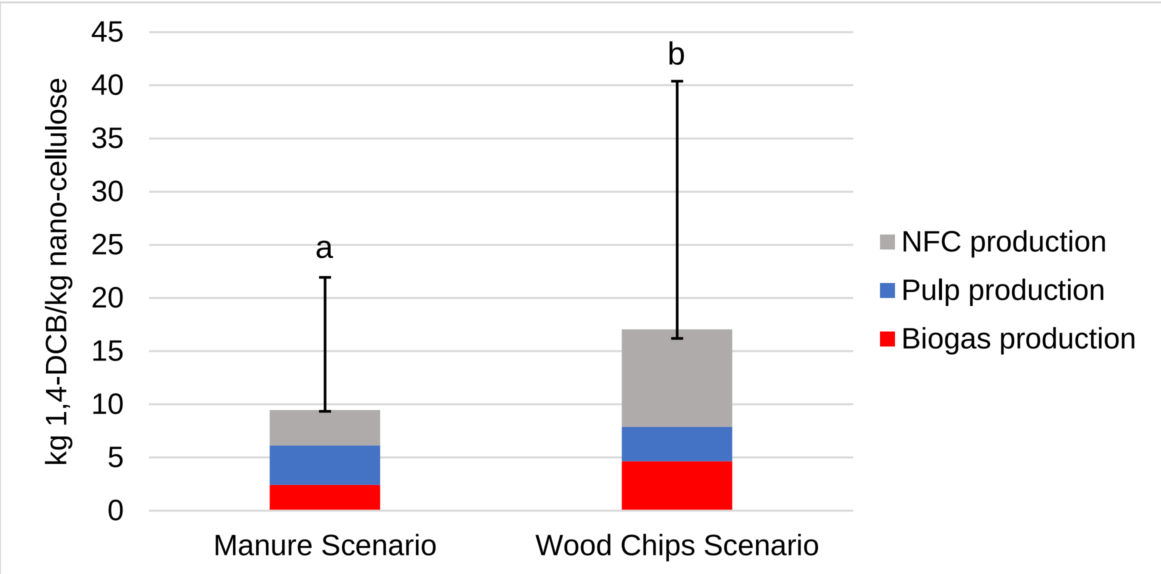

Figure 26: Contribution analysis of the terrestrial ecotoxicity potential of the complete manure and wood chips scenario (n=1.000)

In Figure 26 the absolute values of the terrestrial ecotoxicity potential impact category of the complete manure and wood chips scenario are shown, which is 9,46 kg 1,4-DCB/kg nano-cellulose for the manure scenario and 17,05 kg 1,4-DCB/kg nano-cellulose for the wood chips scenario. The major part of the contribution for the wood chips scenario is coming from the nano-cellulose production (53,74 %) followed by the biogas production (27,26 %) while the highest contribution for the manure scenario is originating from the pulp production (39,24 %) followed by the NFC production (35,11 %).

The highest impact of the NFC production is originating from the needed electricity with the main share coming from copper production and electricity imports from Germany and the Czech Republic. The needed water in the NFC production step is negligible.

In Figure 27 a detailed analysis of the biogas and pulp production for both scenarios is shown. The following percentage values are referring to the median values of the results of the industrial part of both scenarios (see Table 5).

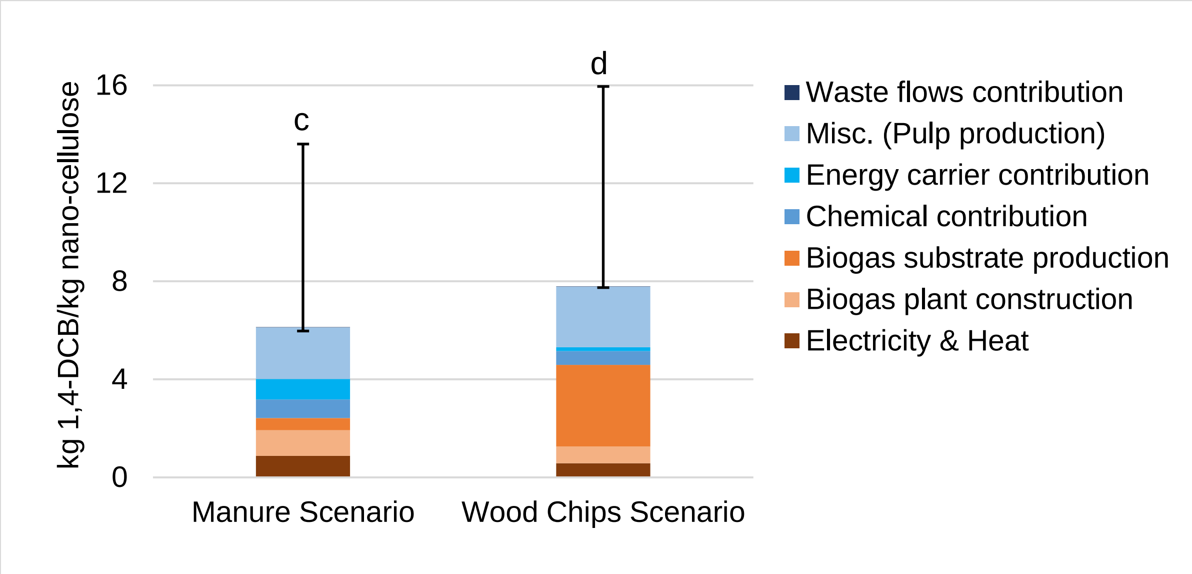

Figure 27: Detailed contribution analysis of the terrestrial ecotoxicity potential of the industrial part of the manure and wood chips scenario (n=1.000); blueish shades = impacts related to pulp production, reddish shades = impacts related to biogas production

The substrate production is contributing the largest share of the wood chips scenario with 42,42 % (3,33 kg 1,4-DCB/kg nano-cellulose), while for the manure scenario the substrate production plays a minor role with a contribution of 8,06 % (0,49 kg 1,4-DCB/kg nano-cellulose).

In the manure scenario the miscellaneous share (includes transports by lorry, ship and train, the construction of the pulp factory and for the wood chips scenario also the production of the pulp wood) has the highest contribution of the industrial part of this scenario with 34,42 %. The transport by lorry and the pulp factory construction are the main contributors in the manure (in total 2,11 kg 1,4-DCB/kg nano-cellulose) and in the wood chips scenario (in total 2,47 kg 1,4-DCB/kg nano-cellulose), respectively.

The biogas plant construction has an impact of 1,05 kg 1,4-DCB/kg nano-cellulose for the manure scenario (17,15 %) and an impact of 0,69 kg 1,4-DCB/kg nano-cellulose for the wood chips scenario (8,74 %). Due to the worse yield by producing nano-cellulose from manure more pulp and therefore a higher share of the biogas plant is needed which explains the difference in absolute values. The biggest impacts have the construction materials concrete and crushed rocks for both scenarios.

The main impact of the chemical contribution (0,56 kg 1,4-DCB/kg nano-cellulose for the manure and 0,44 kg 1,4-DCB/kg nano-cellulose for the wood chips scenario) is originating from sodium hydroxide.

The highest impact of the total contribution originating from energy carriers (0,64 kg 1,4-DCB/kg nano-cellulose for the manure and 0,12 kg 1,4-DCB/kg nano-cellulose for the wood chips scenario) is from the use of wood pellets for the manure scenario and from the use of heavy fuel oil for the wood chips scenario.

The waste flows have an impact of around 0,01 kg 1,4-DCB/kg nano-cellulose for both scenarios and are therefore negligible.

5.2. Results of the sensitivity analysis

In this chapter the results of the four conducted and in chapter 4.6.3 described sensitivity analysis are shown and explained.

(1) NFC production in the industrial scale:

In Figure 28 the relative environmental impact of the NFC production in the manure scenario in the industrial scale and in the laboratory scale for all examined impact categories is shown.

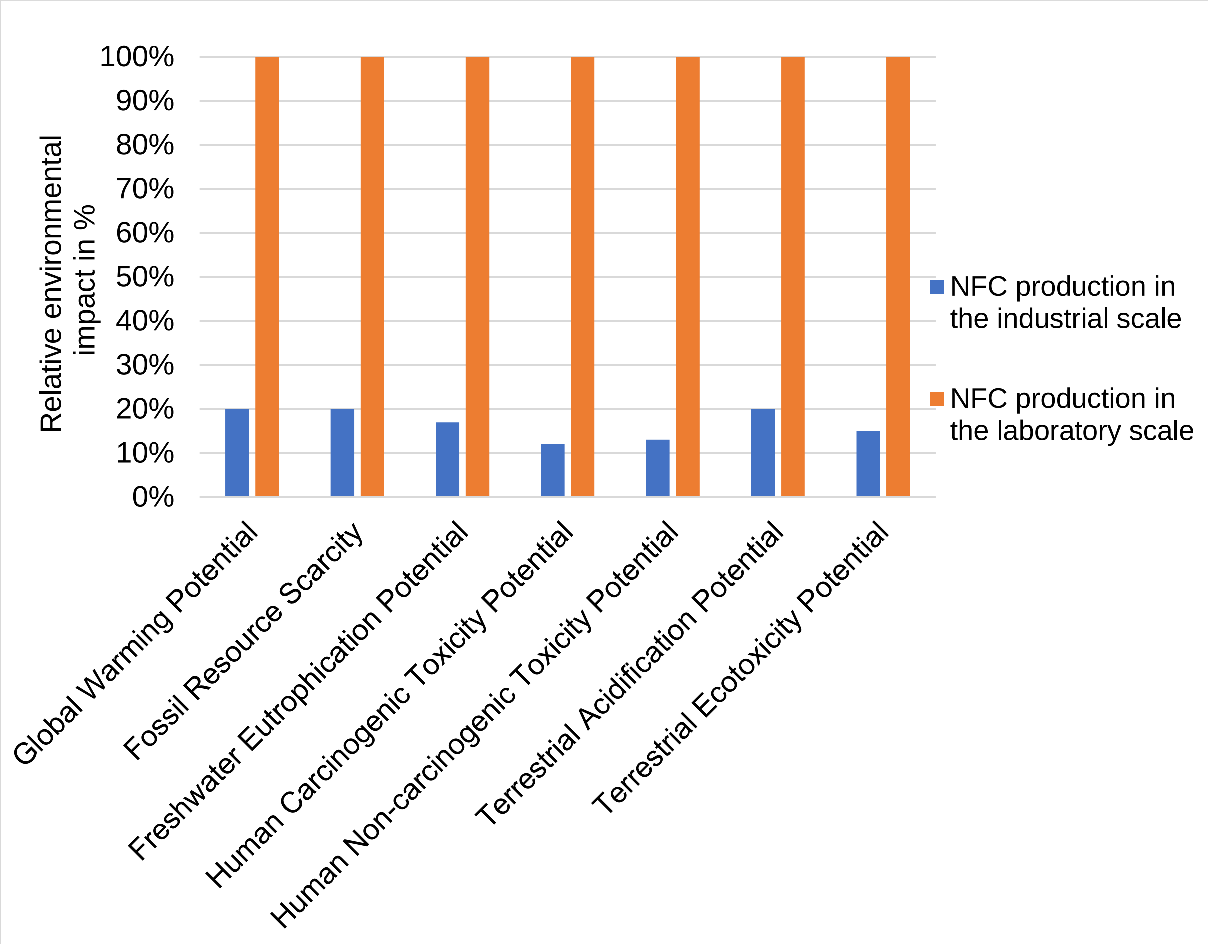

Figure 28: Comparison of the relative environmental impacts of the NFC production in the manure scenario in the industrial scale and in the laboratory scale for all examined impact categories

Figure 28 provides strong evidence that the upscaling of the nano-cellulose production has an essential impact in the manure scenario on overall contributions of the different impact categories. In the manure scenario the highest reduction of the contribution is obtained in the human carcinogenic toxicity potential with a reduction of 87,91 % (from 0,31 kg 1,4-DCB/kg nano-cellulose to 0,04 kg 1,4-DCB/kg nano-cellulose). Likewise, in all other categories a reduction between 80,00 % and 86,91 % is obtained.

The results for the wood chips scenario are shown in Figure 29.

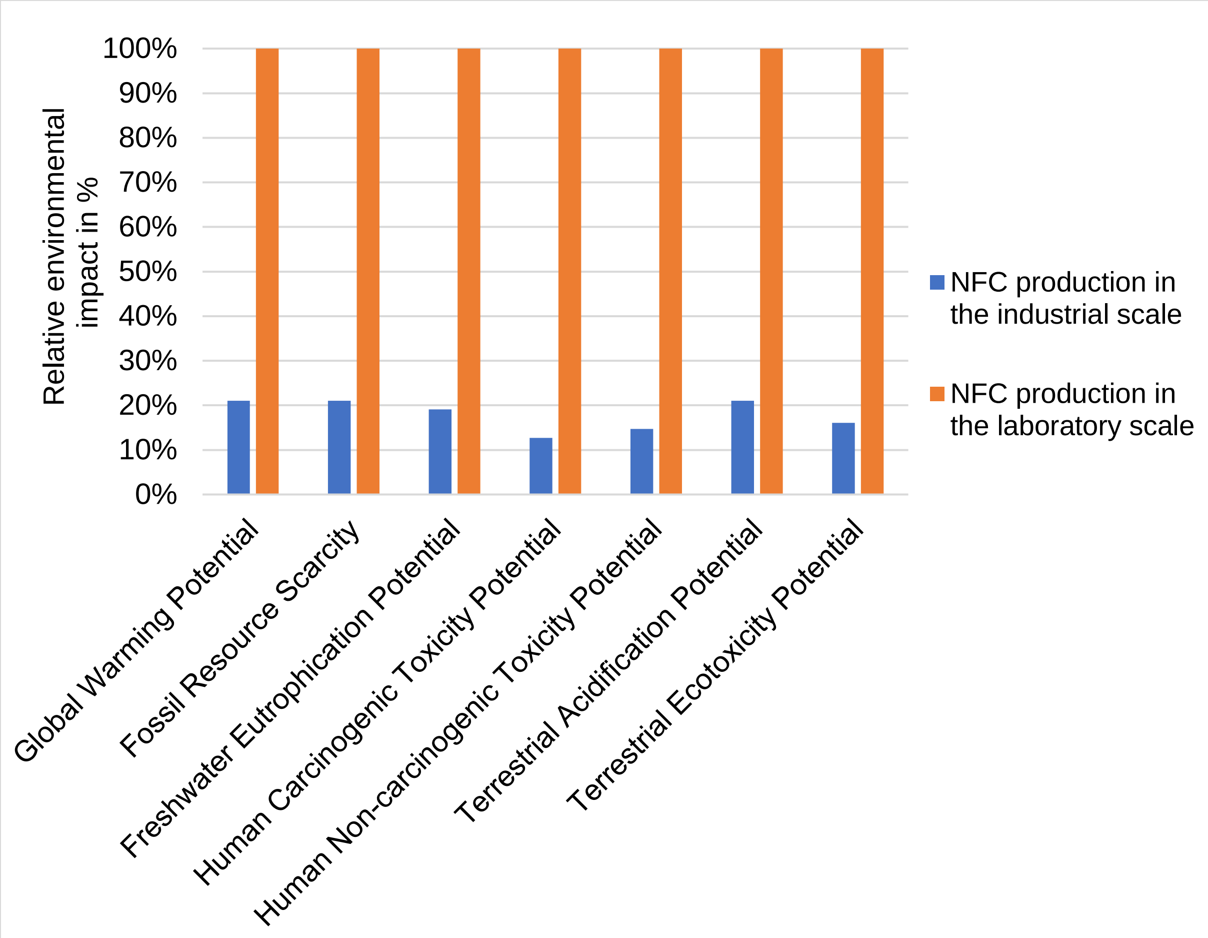

Figure 29: Comparison of the relative environmental impacts of the NFC production in the wood chips scenario in the industrial scale and in the laboratory scale for all examined impact categories

As in the manure scenario the upscaling of the nano-cellulose production has an essential impact to the wood chips scenario. In this scenario the highest reduction of the contribution is obtained in the human carcinogenic toxicity potential with a reduction of 87,29 % (from 0,86 kg 1,4-DCB/kg nano-cellulose to 0,11 kg 1,4-DCB/kg nano-cellulose). Likewise, in all other categories a reduction between 78,96 % and 85,30 % is obtained.

The reduction in both scenarios is possible due to the lower electricity demand for the nano-cellulose production, since this process contributes the most to this step.

(2) GWP credits:

The results of this sensitivity analysis show that a total of 2,29 kg CO_2 eq./kg nano-cellulose can be avoided by using the needed 20,93 kg manure/kg nano-cellulose as an input material for the biogas plant instead of storing it without a cover. Referring to the used biogas plant in the model which has a total input of 17.122 t manure per year a total of 1.875,71 kg CO_2 eq. can be avoided each year.

(3) Self-sufficient biogas plant:

When the heat demand of the biogas plant is covered by the CHP units off-heat this leads to a reduction in the complete manure scenario of under 2 % in FEP, HCTP and HNCTP. The decrease in environmental impact is slightly higher in TEP (3,85 %), FRS (4,59 %) and GWP (5,53 %) with the highest decrease occurring in TAP with a reduction of 10,33 % (0,0014 kg SO_2 eq./kg nano-cellulose). By just referring to the industrial part the reduction in TAP is even higher (21,74 %). This can be justified by the fact that the heat and energy demand have the biggest share in this impact category in the industrial part with 38,08 %.

In the complete wood chips scenario, the reductions are between 0,41 % and 1,66 %. The highest reduction is obtained in the global warming potential with 0,16 kg CO_2 eq./kg nano-cellulose which accounts to a reduction of 10,36 % in the industrial part.

(4) Fertilizer application:

By assuming that the use of fermentation residue (17,13 kg of fertilizer arise due to the production of 1 kg nano-cellulose) as fertilizer in the wood chips scenario is within the system boundaries this leads to higher environmental burdens in the GWP. Additional 0,02 kg CO_2 eq./kg nano-cellulose are emitted to air which results in an increase of GWP of 1,47 % in the industrial part and 0,23 % in the complete scenario. This increase occurs due to the additional burdens from diesel usage for heavy machinery and direct field emissions due to the fertilization. Both are related to additional carbon dioxide and dinitrogen monoxide emissions to air.

12.300 t of fermentation residue occur yearly in the biogas plant used in the wood chips scenario. By using this as fertilizer additional 16.165,3 kg CO_2 eq. are emitted to air per year.

6. Discussion

In this chapter the results of chapter 5 are discussed, put into a broader context and compared with results of literature.

The production of maize silage which is the substrate for the biogas plant in the wood chips scenario is one of the hotspots in the environmental impacts in all categories in this thesis. The substrate production contributes the highest or the second highest share in the biogas production part in the wood chips scenario. In contrast, the substrate production plays a subordinate role in the manure scenario. This is since the cultivation and therefore the use of heavy machines, pesticides and fertilisation with fermentation residue must be considered. This is in line with the findings from Boulamanti et al. (2013) who state that the cultivation of substrate is generally one of the main contributors to environmental impacts. Alike, Zhang, Bi and Clift (2013) and Kral et al. (2016) state that fertilisation with fermentation residue is one of the main contributors. Therefore, one on the main reasons that are decisive for the sustainability of a biogas plant is the used feedstock.

Boulamanti et al. (2013) declare the share of the substrate production with 86 % in the case of terrestrial ecotoxicity and 76 % in the freshwater eutrophication potential. In the terrestrial ecotoxicity potential similar results are found with a share of 72,53 % of the total biogas production. The share of the eutrophication potential is substantially smaller with 26,79 %.

In the impact category terrestrial acidification potential, the fertilisation with fermentation residue, which is part of the maize silage production, is the biggest contributor. Similar results were stated by Kral et al. (2016) who found the substrate production, especially the fertilization with fermentation residue from the used biogas plant, as the main contributor (97 %) related to ammonia emissions which is in line with the presented work. Alike, Fuchsz and Kohlheb (2015) state that biogas plants using energy crops as input material have a higher acidification potential than manure fed biogas plants.

It needs to be pointed out, that the discussion about the pulp production is limited since the processes of kraft pulp production from softwood and hardwood are chosen as proxies for this thesis. Therefore, the analysis is limited by the data depth of the Ecoinvent processes.

One of the hotspots in the pulp production part are the contributions from the four chemicals sodium hydroxide, sulfuric acid, sodium chlorate, oxygen and hydrogen peroxide. Other studies found the impact originating from chemicals also as one of the main contributors to the pulp production(González-García et al., 2011; Ghose and Chinga-Carrasco, 2013; Corcelli et al., 2018). In the carcinogenic and non-carcinogenic human toxicity potential the production of chemicals play a major role in the pulp production and is contributing around 30 % to carcinogenic human toxicity and between 33,53 % and 41,14 % to non-carcinogenic human toxicity. González-García et al. (2011) stated similar values of a contribution of 31 % with the highest share coming from sodium hydroxide and hydrogen peroxide. In this thesis the contribution of sodium chlorate is the highest, although sodium hydroxide and hdrogen peroxide are the second and third biggest contributor. Further the waste flows contribution play a major role in the human carcinogenic toxicity potential with a share of the pulp production of 40,35 % in the manure scenario and 47,59 % in the wood chips scenario. Similar numbers are stated from González-García et al. (2011) who stated this high impact is coming due to the disposal of wood ashes and green liquor dregs on landfills, which is in line with the results of this thesis.

While Lopes et al. (2003) found the eucalyptus production as one of the hotspots due to the fertilisation with glyphosat, this is not the case in this thesis since the pulpwood does not need such a fertilisation.

The discussion of the overall production of NFC is limited due to the use of different assessment methods, the analysis of different impact methods and different system boundaries in the studied papers. In general, the results of this thesis state that the last step of the NFC production is the main contributor. This is due to the impact of the medium voltage electricity used. Even if a rather green Austrian energy mix is used, environmental impacts rise along with the amount of consumption. This is in line with other studies like Turk et al. (2020), Li et al. (2013) and Arvidsson et al. (2015). The results of the sensitivity analysis NFC production in the industrial scale show a tremendous reduction of environmental impacts. This emphasises the importance of analysing a whole product system in the same scale and is also pointed out by Turk et al. (2020) and Piccinno et al. (2018). By assuming that the biogas production is a biological pre-treatment for the nano-cellulose production this part can be compared to other pre-treatments. The main difference is that by using anaerobic digestion as pre-treatment another useful product is provided in contrast to other pre-treatments. The pre-treatments used by other studies, e.g. Turk et al. (2020), Li et al. (2013), Nguyen (2014) and Arvidsson et al. (2015) are usually a mix of chemical and mechanical treatments. Therefore, the main contributor of environmental impacts is the pre-treatment part. This is not the case in this thesis where the biogas production plays a minor role in overall contribution. In contrast, the sensitivity analysis NFC production in the industrial scale demonstrates that the biogas production indeed plays a role in the contribution with shares of around a third to up to half of the total impact in the manure scenario. Nevertheless, the second output by using this pre-treatment, the biogas, must be taken into consideration as it can be used as a source of green energy.

Arvidsson et al. (2015) stated that the pulp production has an impact of 0,39 kg CO_2 eq./kg nano-cellulose, the pre-treatment has an impact of 0,30 kg CO_2 eq./kg nano-cellulose for the enzymatic route and 0,97 kg CO_2 eq./kg nano-cellulose for the carboxymethylation route. The results for the pulp production of that study are in line with the results of the manure and wood chips scenario (0,46 kg CO_2 eq./kg nano-cellulose and 0,41 kg CO_2 eq./kg nano-cellulose, respectively). Further, the treatment of the NFC production is quite higher in the manure scenario than in the study from Arvidsson et al. (2015) due to the higher electricity demand.

Sun et al. (2013) estimated the global warming potential of their NFC used as reinforcement of polypropylene with 1,2 – 3,7 kg CO_2 eq./kg nano-cellulose. The impact of the manure scenario to GWP100 of this thesis is 4,41 kg CO_2 eq./kg nano-cellulose which is indeed higher but is related to a multi-output process delivering nano-cellulose and biogas

Turk et al. (2020) used thermo-groundwood as starting material and used a Soxhlet extraction process. This specific process was found to be the main contributor to all the impact categories. In the global warming potential high results of 806,92 kg CO_2 eq./kg nano-cellulose were stated which is two magnitudes higher than the results of the manure and wood chips scenario. This is since the Soxhlet extraction has a high energy demand and includes two additional purification steps. Further, the study was conducted in the laboratory scale (Turk et al., 2020). These factors explain the results in the impact categories freshwater eutrophication, human carcinogenic human toxicity and in the terrestrial acidification potential which are two magnitudes higher. In the non-carcinogenic human-toxicity potential the magnitude is even three times higher. This is due to the high chemical demand in the Soxhlet extraction. In the terrestrial ecotoxicity potential the impact in the study of Turk et al. (2020) are found to be lower with 5,60 kg 1,4-DB eq./kg nano-cellulose than in the manure scenario with 9,46 kg 1,4-DB eq./kg nano-cellulose. This arises since the transport by lorry and the pulp factory construction have an essential role by contributing 39,08 % and 26,49 % for the manure scenario.

7. Conclusion

The production of NFC from the fermentation residue of anaerobically digested elephant manure is a new approach. This thesis points out that by using elephant manure as starting material the environmental impacts can be drastically reduced in all the examined impact categories. Further, this fabrication route is a multi-output process by not only providing nano-cellulose but also biogas. The GWP is 4,41 kg CO_2 eq./kg NFC in the manure scenario and 9,74 kg CO_2 eq./kg NFC in the wood chips scenario. The main contributor in both scenarios is the NFC production from pulp by grinding (66,64 % in the manure scenario and 84,42 % in the wood chips scenario). The needed electricity contributes for both scenarios 99 % to this step. In the manure scenario the biogas production contributes 22,25 % (0,98 kg CO_2 eq./kg nano-cellulose) to the total GWP, while the pulp production plays a smaller role with around half the contribution of 11,11 % (0,49 kg CO_2 eq./kg nano-cellulose). Similar proportions in the percentage distribution but higher absolute values are found in the wood chips scenario where the biogas production contributes 10,78 % (1,05 kg CO_2 eq./kg nano-cellulose) to the total GWP and the pulp production 4,80 % (0,47 kg CO_2 eq./kg nano-cellulose).

In all impact categories one of the hotspots is the energy demand in the last fabrication step, the grinding step from pulp to nano-cellulose. This is in line with other studies. Since this thesis is in the laboratory and in the industrial scale it points out the factors that must be taken a closer look at by planning a real industrial site for producing nano-cellulose.

Overall, the LCA shows that the environmental burdens occurring during the production of NFC from hardwood chips can be drastically reduced by using elephant manure which makes it a sustainable alternative. Furthermore, the new approach is a multi-output process by providing NFC and biogas. The new fabrication route still needs more research but has great potential, especially by considering other manure resources as starting material, e.g. cattle or pig manure.

8. Limitations and outlook

This chapter should point out that a life cycle assessment is always just an approach to real circumstances. The examined life cycle assessment is based on some assumptions which affect the results. Since the manure scenario is not executed in the industrial scale yet, proxies needed to be chosen. Although, the proxy approach provides a first good overview of what environmental impacts could look like, it is lacking behind by using data from a real production site. The chemical treatment of the pulp from fermented elephant manure still needs improvement, especially when upscaled to an industrial scale.

The system boundaries setting is a subjective process that is different in various studies. Especially in this thesis the usage of the produced biogas, e.g. by producing electricity and heat with a CHP, could be included in the product system and would provide more information on the environmental impacts.

More research is also needed about the nutrient availability of the by-product from the pulp production that can be used as fertilizer. Then, the fertilizer application could be included in the product system since this is a potential high contributor to various impact categories (e.g. terrestrial acidification potential). On the other hand, this fertiliser would replace other fertilisers for biogas substrate production which means that the actual impacts must be studied carefully.

By using the kraft pulp production from softwood and hardwood as proxies for the manure and wood chips scenario, respectively the data quality is prescribed by the

Ecoinvent database. Therefore, for this thesis an aggregation of two bleaching procedures, the total chlorine free and the elemental chlorine free procedure, must be assumed. Usually, a pulp production site would specify the use of one of these methods.

One big point is the usage of elephant manure as starting material. The usage would make sense in countries with big elephant populations, but not in European countries. As explained in chapter 3, one of the goals of this thesis is to give a basis for further research of the production of nano-cellulose from manure from different animals, like cattle or pig. By assuming an occurrence of 3 t of solid manure/per year and cattle (Bayerische Landesanstalt für Landwirtschaft, 2019) and further assuming that the same amount of elephant manure and cattle manure is needed for the nano-cellulose production, a total production of 125,68 kg nano-cellulose per cattle/year could be possible.

9. Summary

Nano-cellulose is a unique new material with a wide range of potential applications and promising properties. Still, the research of the environmental impacts of the production of this material in the industrial scale is scarce. Nano-cellulose is often produced from pulp, which is an energy and water intensive process. Further, the pulp to nano-cellulose step requires a lot of energy. In this work the new approach to produce nano-cellulose from the fermentation residue of anaerobically digested elephant manure (manure scenario) is compared to the production from kraft pulp from wood chips (wood chips scenario). Since the manure scenario is currently only executed in the laboratory a proxy approach is used to upscale it to the industrial scale to ensure comparability with the highly industrialised kraft process. No appropriate proxy was found for the pulp to nano-cellulose step, the grinding step, and is therefore not upscaled. Since the manure scenario is a multi-output process, providing biogas and nano-cellulose a typical Austrian biogas plant with maize silage and pig slurry as input material is added to the wood chips scenario for equal benefits. Seven impact categories (global warming potential, fossil resource scarcity, freshwater eutrophication, human carcinogenic and non-carcinogenic toxicity potential, terrestrial

acidification potential and terrestrial ecotoxicity potential) are analysed with the Recipe2016 (H) method, the software openLCA and the Ecoinvent database v.3.6.

The results show that the manure scenario has lower impacts in all the assessed impact categories being mostly only around half of the impact of the wood chips scenario (between 43,70 % and 55,51 % of the impact of the wood chips scenario), respectively. A tremendous difference between the scenarios is in the terrestrial acidification potential, where the impact of the manure scenario is just 17,42 % of the impact of the wood chips scenario. This difference originates from the production of maize silage for the biogas plant, especially from the fertilisation with fermentation residue.

The global warming potential is 4,41 kg CO_2 eq./kg nano-cellulose for the manure and 9,74 kg CO_2 eq./kg nano-cellulose for the wood chips scenario. The pulp to nano-cellulose step is found to be a hotspot due to the high electricity demand in both scenarios which is in line with other studies. The grinding step contributes between 35,11 % (terrestrial ecotoxicity potential) and 81,49 % (freshwater eutrophication potential) to the total environmental impact in the manure scenario and between 21,79 % (terrestrial acidification potential) and 93,38 % (freshwater eutrophication potential) in the wood chips scenario. The electricity demand contributes 99,9 % to the grinding step. An essential share is originating also from the heat and energy demand of the biogas plant in both scenarios and from the pulpwood production in the wood chips scenario.

Further, the maize silage production for the biogas plant in the wood chips scenario is another hotspot especially in the terrestrial acidification potential category where it contributes a share of 78,25 % in the industrial part, which includes the biogas and pulp production.

By comparing the results to literature the maize silage production (especially the fertilization with the fermentation residue) is found to be a hotspot in various studies too, e.g. Boulamanti et al. (2013), Zhang, Bi and Clift (2013) and Fuchsz and Kohlheb (2015). Especially the terrestrial acidification potential is affected by this process.

In the pulp production process the chemicals are the main contributor to environmental impacts in this thesis, as well as in other related studies, e.g. González-García et al. (2011), Ghose and Chinga-Carrasco (2013). In the carcinogenic and non-carcinogenic human toxicity potential the production of chemicals plays a major role in the pulp production and is contributing around 30 % to the carcinogenic human toxicity and between 33,53 % and 41,14 % to the non-carcinogenic human toxicity. Similar values are given by González-García et al. (2011). In the present thesis the contribution of sodium chlorate is the highest, followed by sodium hydroxide, oxygen and hydrogen peroxide.

The waste flows contribution play a major role in the human carcinogenic toxicity potential with a share of the pulp production of 40,35 % in the manure scenario and of 47,59 % in the wood chips scenario. Similar numbers are stated from González-García et al. (2011).

In general, this LCA shows that the production of NFC from elephant manure is a sustainable alternative to the production of NFC from wood chips by also providing biogas as second output and additional energy source.

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Appendix I

Biogas production in the manure scenario

Table 11: Data for the biogas production from elephant manure from laboratory experiments at the institute of agricultural engineering at the University of Natural Resources and Life Sciences

Retention time	**DM**	**oDM**	**Biogas yield**	**Standard deviation**	**Methane yield**	**Standard deviation**	**Storage density**
[days]	[% FM]	[% DM]	[Nm^3/t oDM]	[Nm^3/t oDM]	[Nm^3/t oDM]	[Nm^3/t oDM]	[m^3/t FM]
21,77	9,72	89,03	360,59	11,29	218,97	6,78	1,00

The used fermenter has a volume of 2.701 m^3 (Kral *et al.*, 2016), a safety margin of 15 % is assumed which leads to a total useable volume of 2.348,70 m^3. The daily fresh matter input volume is calculated with the formula from Fachagentur nachwachsende Rohstoffe (2016):

$$\dot{V} = \frac{V_R}{HRT}$$

$\dot{\mathbf{V}}$: daily fresh matter input volume, m^3 per day

$\mathbf{V_R}$: useable fermenter volume, m^3

HRT: hydraulic retention time, days

Therefore, the daily fresh matter input volume is 107,90 m^3 per day. Since the storage density is assumed to be 1 m^3/t fresh matter, this leads to a total daily input of 107,90 t FM per day. The elephant manure originally has a dry matter content of 22,4 %, but for better performance it is diluted to 9,72 % dry matter content. The total fresh matter input of elephant manure per day is 46,91 t, so a total of 60,98 t of water per day is needed for dilution. The dry matter content elephant manure input per day is 10,49 t, the total organic dry matter content input per day is 9,34 t,

The yearly fresh matter input of elephant manure is 17.122,79 t, so 22.259,50 t of freshwater are needed per year.

Based on the data from Table 11 a total of 3.367,61 Nm^3 Biogas per day and 1.229.177,02 Nm^3 Biogas per year are produced, referring to the organic dry matter content respectively. The methane content in the biogas is 60,72 %, which leads to a methane production of 2.044,96 Nm^3 per day and 746.410,73 Nm^3 per year, referring to the organic dry matter content respectively.

According to Bachmaier (2012) 0,2 % of the produced methane is leaking from the fermenter, which leads to a total methane leakage of 1.492,82 Nm^3 per year referring to the organic dry matter content.

Laboratory experiments showed that the organic material is degraded by 63,72 % during the fermentation process, leading to a total of 37.206,58458 t/a of fermentation residue with a dry matter content of 4,41 % and organic dry matter content of 3,31 %.

Appendix II

Biogas production in the wood chips scenario

A typical Austrian biogas plant is modelled for this master thesis. Therefore, as input material 70 % maize silage (33 % dry matter content) and 30 % pig slurry (6 % dry matter content) are used, percentages are referring to fresh matter. Other important data of the input material is listed below in Table 12.

Table 12: Data for the biogas production from maize silage and pig slurry (Fachagentur nachwachsende Rohstoffe, 2016)

	Probability distribution	DM [%]	oDM [%]	Biogas yield [Nm³/t oDM]	Methane yield [Nm³/t oDM]	Storage density [m³/t FM]
Maize silage	Triangular	28-35	85-98	443-691	234-364	1,22
Pig slurry	Triangular	4-7	75-86	341-638	180-360	1

The used fermenter has a volume of 2.701 m³ (Kral *et al.*, 2016), a safety margin of 15 % is assumed which leads to a total useable volume of 2.348,70 m³. The retention time is assumed to be 50 days. The daily fresh matter input volume is calculated with the formula from Fachagentur nachwachsende Rohstoffe (2016):

$$\dot{V} = \frac{V_R}{HRT}$$

$\dot{\mathbf{V}}$: daily fresh matter input volume, m³ per day

$\mathbf{V_R}$: useable fermenter volume, m³

HRT: hydraulic retention time, days

Therefore, the daily fresh matter input volume is 46,97 m³ per day. Since the storage density is 1,22 m³/t fresh matter for maize silage and 1 m³/t fresh matter for pig slurry and considering the aimed input of 70 % maize silage and 30 % pig slurry referring to the fresh matter, this leads to a total daily input of 29 t FM maize silage and 12,17 t FM pig slurry per day, respectively. The dry matter content input per day is 9,57 t maize silage and 0,73 t pig slurry, the organic dry content matter input per day is 9,09 t maize silage and 0,58 t pig slurry.

The yearly input of maize silage is 10.585 t FM and 4.443,48 t pig slurry.

The biogas plant produces on average of 2.211.522,61828 Nm^3/a biogas referring to the organic dry matter content of the input material, the methane content in the biogas is on average 53,43 %. According to Bachmaier (2012) 0,2 % of the produced methane is leaking from the fermenter, which leads to a total methane leakage of 2.363,15 Nm^3 per year referring to the organic dry matter content.

Further, 78 % of the organic material is degraded during the fermentation, leading to a total of 12.287,89112 t/a of fermentation residue with a dry matter content of 8,29 % and organic dry matter content of 6,44 %.

Appendix III

Table 13: Results of the Wilcoxon rank-sum test for the manure and wood-chip scenario

	Impact category	Asymptotic significance	Z-value
Industrial parts	Global Warming Potential	0,000	-18,459
Industrial parts	Fossil Resource Scarcity	0,000	-6,114
Industrial parts	Freshwater Eutrophication Potential	0,000	-3,939
Industrial parts	Human Carcinogenic Toxicity Potential	0,000	-5,292
Industrial parts	Human non-carcinogenic Toxicity Potential	0,345	-0,943
Industrial parts	Terrestrial Acidification Potential	0,000	-27,239
Industrial parts	Terrestrial Ecotoxicity Potential	0,000	-18,479
Complete scenarios	Global Warming Potential	0,000	-27,392
Complete scenarios	Fossil Resource Scarcity	0,000	-27,334
Complete scenarios	Freshwater Eutrophication Potential	0,000	-24,138
Complete scenarios	Human Carcinogenic Toxicity Potential	0,000	13,336
Complete scenarios	Human non-carcinogenic Toxicity Potential	0,000	-20,930
Complete scenarios	Terrestrial Acidification Potential	0,000	-27,371
Complete scenarios	Terrestrial Ecotoxicity Potential	0,000	-26,152