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Assessing the Nitrogen Recovery Potential of Recycling Fertilizers from Human Excreta using Thermophilic Composting in the Barnim Region : A Scenario Study based on Material Flow Analysis

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Abstract

Understanding the interactions between agricultural and human activities in terms of nutrient transformation, utilization and loss is essential for promoting sustainable regional development. Recently, there has been a growing interest in recycling human excreta for fertilizer production. To estimate this potential and assess the feasibility of complete replacement of mineral fertilizers, this study conducted a delicate material and nitrogen (N) flows analysis (both in the human and agricultural sectors) for 2016 and 2020, based on the region of Barnim, Brandenburg, Germany. Agriculture is the sector with the highest N flows, mainly contributed by harvested crops. It is noteworthy that the N surplus in Barnim soils decreases from 441 kg N/a in 2016 to 81 kg N/a in 2020, showing a trend below the German national average. The sensitivity of the system revolves around nitrogen losses during fertilization and the input of mineral fertilizers. Theoretically, a region-wide separate collection of feces and urine could assist in recovering 20.9 % of nitrogen from the human excreta and wastewater section, resulting in a 44.1% mineral fertilizer replacement rate (53.6 % in the maximal replacement scenario) . Conversely, from a technical point of view, 4.5 % of nitrogen can be recovered for a replacement rate of 3.8 % (13.3% in the maximal replacement scenario). The recycling of urine and feces exhibits potential in advancing the closure of the nitrogen loop in the Barnim region.

Key words: Dry toilet, recycled fertilizer from human excreta, Material flow analysis, nitrogen management, scenario study, nitrogen recovery, mineral fertilizer substitution potential, agriculture

Zusammenfassung

Das Verständnis der Wechselwirkungen zwischen landwirtschaftlichen und menschlichen Tätigkeiten in Bezug auf die Umwandlung, Nutzung und den Verlust von Nährstoffen ist für die Förderung einer nachhaltigen regionalen Entwicklung von wesentlicher Bedeutung. In jüngster Zeit ist das Interesse an der Wiederverwertung menschlicher Ausscheidungen für die Düngemittelproduktion gestiegen. Um dieses Potenzial abzuschätzen und die Machbarkeit eines vollständigen Ersatzes von Mineraldünger zu bewerten, wurde in dieser Arbeit eine Analyse der Stoff- und Stickstoffflüsse (sowohl im menschlichen als auch im landwirtschaftlichen Sektor) für die Jahre 2016 und 2020 auf der Grundlage der Region Barnim, Brandenburg, Deutschland, durchgeführt. Die Landwirtschaft ist der Sektor mit den höchsten Stickstoffflüssen, die hauptsächlich durch die Ernte von Getreide verursacht werden. Bemerkenswert ist, dass der N-Überschuss in den Barnimer Böden von 441 kg N/a im Jahr 2016 auf 81 kg N/a im Jahr 2020 gesunken ist und damit unter dem Bundesdurchschnitt liegt. Die Sensibilität des Systems dreht sich um die Stickstoffverluste bei der Düngung und den Eintrag von Mineraldüngern. Theoretisch könnte eine flächendeckende getrennte Sammlung von Fäkalien und Urin dazu beitragen, 20,9 % des Stickstoffs aus den menschlichen Ausscheidungen und dem Abwasser zurückzugewinnen, was zu einer Mineraldüngerersatzrate von 44,1 % führt (53,6 % im maximalen Ersatzszenario). Umgekehrt können aus technischer Sicht 4,5 % des Stickstoffs zurückgewonnen werden, was einer Ersatzrate von 3,8 % entspricht (13,3 % im Szenario des maximalen Ersatzes). Das Recycling von Urin und Fäkalien hat das Potenzial, die Schließung des Stickstoffkreislaufs in der Barnim-Region zu fördern.

Schlüsselwörter: Trockentoilette, Recyclingdünger aus menschlichen Ausscheidungen, Stoffstromanalyse, Stickstoffmanagement, Szenarioanalyse, Stickstoffrückgewinnung, Mineraldüngersubstitutionspotenzial, Landwirtschaft

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1. Introduction

Global warming and consequent climate change are of utmost concern to the world. This is evidenced by the latest report of the Intergovernmental Panel on Climate Change (IPCC), which shows that global surface temperatures increased by 1.09 [0.95 to 1.20] °C in 2011 - 2020 compared to the 1850 - 1900 baseline (Lee et al. 2023). This climate change will not only affect human health and the economy, but also put pressure on agriculture, forestry, fisheries and aquaculture. (Bezner et al. 2022)

One of the centers of the climate discussion is the significant impact of agriculture on global warming. Specifically, Agriculture, Forestry and Other Land Use (AFOLU) accounts for about a quarter of total net anthropogenic GHG emissions (IPCC 2019). Under these circumstances, the increasing global consumption of chemical fertilizer (also known as mineral fertilizer, artificial fertilizer) in agricultural, which has surged from around 12 million tons in 1961 to 110 million tons in 2018 (Rodríguez-Espinosa et al. 2023), poses a major challenge. Excessive use of mineral fertilizers not only risks pollution from surface water runoff (Vries et al. 2022), but also increase the agricultural intensification (Golia et al. 2009). In view of the many challenges faced and the need to conserve primary raw materials, it is urgent to find sustainable alternative solutions to mineral fertilizers.

In this context, Europe is not passive. The Farm to Fork Strategy stipulates that by 2030, 25% of the agricultural land in EU must be organic farm (EUGreenDeal 2020). The strategy also calls for a 50% reduction in nutrient loss to ensure soil fertility, which in turn requires a 20% reduction in fertilizer use (EUGreenDeal 2020). Germany has also taken corresponding measures to curb nitrogen and phosphorus emissions from agriculture, notably through the Fertilizer Ordinance (DüV).

Transition from mineral to organic fertilizers is one possible solution. The use of mineral fertilizers allow a quick absorption of nutrients by the plants, but in a limited amount (Kumar et al. 2022). Over-application often contaminates water sources. In contrast, organic fertilizers offer an opportunity to conserve raw materials while promoting waste hierarchy (prevention, reuse, recycling, recovery and disposal). Therefore, recovery of nutrients from biowaste and wastewater is becoming an important consideration.

Among the various alternatives, the recycling of nutrients from human excreta into agriculture is gaining momentum as highlighted by (Dawson and Hilton 2011). Human excreta is rich in nitrogen (Rose et al. 2015) and has the dual advantage of being nutrient-rich, small volume, and has the opportunity to reduce the burden on wastewater treatment plants. However, the use of human feces and urine remains a controversial topic, especially in Germany and throughout Europe. Despite the great potential, concerns related to hygiene and pathogens (Heinonen-Tanski and van Wijk-Sijbesma 2005) hinder its integration into agriculture. In Germany, for example, feces and urine from dry toilets cannot be recycled in relation to the soil, as there is no clear legal regulations exist. (Korduan 2020)

In this context, a pilot plant for human waste recycling using thermophilic composting technology has been built in Barnim, Brandenburg, Germany. Although the outlook is promising, a comprehensive material and nutrient flow analysis of human activities and agriculture in Barnim remains unavailable. The present study aims to fill this gap, with a particular focus on nitrogen, which is a key element for life and a critical parameter for assessing fertilizer quality.

Research question

- What is the potential for nitrogen recovery from human excreta?
- What is the potential for replacing mineral fertilizers with recycled fertilizers?
- What is the status of nitrogen in Barnim soils?

The key to this thesis is to study the material and nitrogen flows from human metabolism and agricultural activities in Barnim from an exhaustive point of view using material flow and material flow analysis methods.

Research objectives

- To comprehensively map the pathways of the material and nitrogen flows in the Barnim region.
- To assess temporal changes in nitrogen storage in soil in Barnim.
- Explore nitrogen dynamics associated with composting of human excreta.
- To assess the feasibility of replacing mineral fertilizers with recycled fertilizer from human excreta.
- Consider policy shifts, technological advances, and demographic changes to project future nitrogen recovery potential.
- Conduct a sensitivity analysis to identify the major flows influencing soil nitrogen stock.

Thesis Structure

Chapter 2 will delve into the background, elucidating the nitrogen cycle, fertilizer use, dry toilet systems and related technologies. Chapter 3 will illustrate the methodology, scenario analysis and calculations used. Chapter 4 will present the results of the material flow analysis, and Chapter 5 will compare scenarios, analyze sensitivities, and discuss the limitations and possible improvements of the study. Chapter 6 will summarize the conclusions drawn from this study as well as suggest possible directions for future research.

In order to provide a better understanding of this study, the following supplementary documents are provided digitally.

1. The raw calculation datasheet: [Raw calculation datasheet.xlsx]
2. Flow charts of the 5 scenarios (picture.png)
3. STAN models of the 5 scenarios (STAN file.zmfa)
4. The summary of the model results [Result sheet.xlsx]

2. Background

2.1. Nitrogen cycle and fertilizers

2.1.1. Nitrogen cycle

Nitrogen, as the necessary component of proteins, DNA, etc., contributes approximately 80 % of gaseous components of the atmosphere (Bernhard 2020). It is conserved as one of the most critical elements for the survival of lives (Bernhard 2020).

Figure 2-1 depicts the nitrogen cycle in an agricultural scale. Crops absorb nitrogen primarily from the soil, which is facilitated by atmospheric nitrogen fixation as well as precipitation and atmospheric deposition. The nitrogen stock of the soil is a combination of inherent soil nutrients and added fertilizers that contribute to nitrogen uptake. The main form of nitrogen utilized by crops is nitrite, either directly from mineral fertilizers or through mineralization of soil organic matter. However, nitrite easily escapes to the atmosphere by leaching into groundwater or through the denitrification process. In addition, nitrite can be reincorporated into organic matter through fixation processes. Runoff activities are another important pathway for nitrogen loss in this system. Livestock manure also contributes to nitrogen inputs, and depending on how it is handled - whether it is left in the field, stored in containers, or treated- can result in nitrogen loss (Bai et al. 2016). Both manure and soil will emit gaseous nitrogen as NO_x, NH_3. As the harvesting season ends and crops are harvested and removed for production, the residue left behind retains some of the nitrogen in the soil, thus providing soil extra nutrient for future agricultural production.

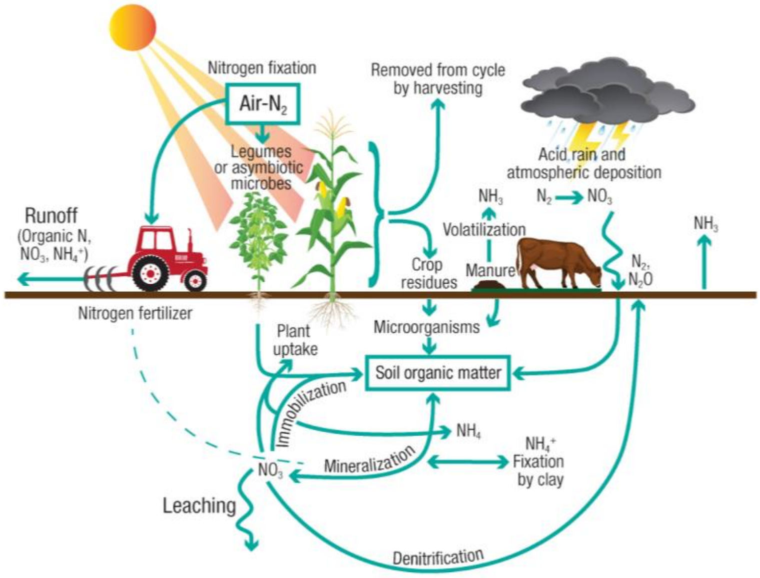


Figure 2-1 Nitrogen flows in agriculture (Guertal 2021)

However, since the mid-1900s, human activities such as fertilizer production has considerably affected the nitrogen fixation in ecosystems, which leads to the alteration of nitrogen cycle

(Galloway 1998). In the nature, plants can only uptake NH_4^+ and NO_3^- as nitrogen supply. However, it is an energy intensive process to fix and recycle nitrogen by bacterium (Langenfeld et al. 2021) **.** Surplus nitrogen can lead to over-stimulation of aquatic plants and algae growth. The algae not only consume dissolved oxygen through respiration, but also block the lake surface and prevent light from entering due to overgrowth. Fishes will die due to the lack of oxygen, leading to a further deterioration of water quality(Amorim and Moura 2021). In addition, excessive nitric acid in water bodies can directly affect people's health (Brender 2020). Therefore, the EU Drinking Water Directive stipulates that the NO_3^- concentration threshold in groundwater should be less than 50 mg/l. In the sewage system, nitrogen compounds will be removed mainly by nitrification and denitrification process. It will be first oxidized to nitrate the reduced, and released to the atmosphere as nitrogen gas (Okabe et al. 2011).

2.1.2. Closing N-loop

The idea of a closed nitrogen cycle is to avoid any loss of nitrogen by using waste as a resource (Kara et al. 2022). Starting with agricultural waste, animal manure and crop residues can be collected and treated. The nitrogen-rich residue will be used as fertilizer and added to crops. The harvested crops will be transported to the city or be consumed on the farm. In this way, nitrogen is excreted in manure, transformed as fertilizer, entered into crops, and ultimately into the human body. The fertilizer application process may result in the loss of nitrogen to groundwater and the atmosphere. In order to close the loop, loss and emissions should be avoided to the largest extent. (Wallentine et al. 2023)

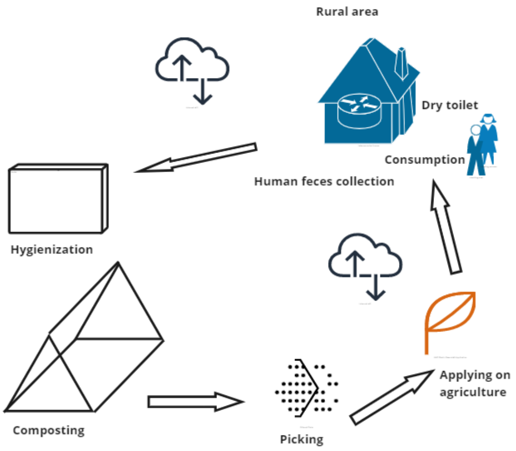


Figure 2-2 Ideal closed nitrogen loop in rural area with the recycling of human excreta

Moreover, some of the nitrogen in the atmosphere can be biologically fixed by plants. Similarly, the nitrogen in the harvest is partially consumed in the region and partially being exported to the other regions. Biowaste and garden waste can be composted and returned to agricultural land. In this way, the demand for mineral fertilizers, which require the extraction of raw materials, declines. In some places, human excreta can be collected through dry toilet systems and used as a nitrogen resource for horticulture (regulations for composting applications of human excreta may vary from country to country). As a result, the nitrogen cycle linking urban and rural areas is closed, thus providing better nutritional prospects.

Figure 2-2 shows an ideal case of closing the nitrogen loop by recycling the excreta from human.

2.1.3. Fertilizer

Different fertilizers used in agriculture

Fertilizers are a vital part of modern agriculture. The main reason is that fertilizers are effective in increasing crop yields, which leads to higher economic profits. (McArthur and McCord 2017)

Fertilizer inputs in agriculture come from different sources. The main fertilizer inputs continue to be chemical/mineral fertilizers, which have a rapid impact on crops. Depending on the livestock sector, livestock manure can also be mixed with rice straw used as livestock bedding. (Häußermann et al. 2020) On farms, intercrops can be used as green fertilizer (Jensen et al. 2020). In addition, fertilizers come from human and municipal activities. This refers to the organic fraction of municipal solid waste and green waste, which can be composted or treated under anaerobic conditions to produce fertilizer. In addition, sewage sludge can also be used as fertilizer after treatment to support crop production. (Häußermann et al. 2020)

Problem with mineral fertilizer

In Germany, around half of the fertilizer is supported by mineral fertilizer (Häußermann et al. 2020) . Mineral fertilizer is widely used and highly being dependent, which will lead to a lot of further problems.

The conventional application of chemical fertilizer lead to poor nutrient absorption efficiency and notable loss (Rawal et al. 2023). In addition, due to the level of education, farming experience and the promotion of agrochemicals, farmers always over-apply fertilizers instead of applying them as needed. (Hoque et al. 2022). Additionally, long-term utilization of chemical fertilizer will have a negative impact on environment, especially water body. In China, a large quantity of nitrogen fertilizer, which is applied to winter wheat or summer maize, results in the groundwater pollution of N. The N leaching is particularly evident caused by over-fertilization during the high-intensity rainfalls seasons (Mo et al. 2022). Leaching will also lead to high concentration of phosphorus, which is the main cause of water eutrophication (Hussain et al. 2021). Another negative impact is on the soil. According to Villamil, long-term application leads to acidification, which affects the biological properties of the soil and possibly inhibits nitrogen fixation (Villamil et al. 2021). The long-term chemical fertilization application will cause soil compaction as well. When the soil becomes too dense, the plant's root system is unable to grow further, leading to poor soil drainage. (Pahalvi et al. 2021) Furthermore utilization of nitrogen fertilizer causes the emission of gaseous NO_2 to the atmosphere. 43 % of agriculture emissions and 3.9 % of the total anthropogenic emissions in EU are due to the use of nitrogen fertilizer.(EAA 2019)

2.2. Dry toilet systems

2.2.1. Dry toilet

Dry toilets, also known as composting toilets, do not use water or liquids for flushing and transportation of human excreta (see Figure 2-3). It is therefore suitable for use in areas where water supply and sewerage connections are not available. (Berger 2010) The dry system was first invented by Rickard Lidstrom in 1939 and has since been widely used in developing countries and rural areas. (Aburto-Medina et al. 2020)

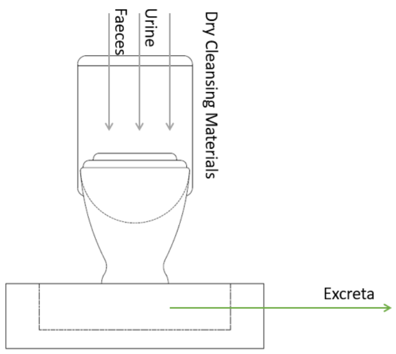


Figure 2-3 Schematic drawing of a dry toilet system

The dry latrines are commonly over pits. They are suitable for both sitters and squatters (Tilley et al. 2014). Excreta can be composted directly in a vault placed under the toilet collected and transported to another location for further processing (Lourenço and Nunes 2020). Generally, a toilet part and a composting part constitute a dry toilet (Anand and Apul 2014). The usual size of the vault volume is at least 1 m^3 and the storage time is designed to be at least 60 days for ensuring the temperature increase (Rose and Jiménez Cisneros 2019).

Except for the two main components, a vent pipe and drain are typically designed and installed in order to prevent the odor and leachate. The ventilation pipe is installed straight in the toilet and generally reach 0.3-0.5 m above the top of the toilet. A screen can be also placed for the purpose of insect prevention. (Lopez Zavala and FUNAMIZU 2006) Besides, sawdust, leaves and food scraps are normally used as bulking matrix to adjust waste and modify C/N ratio as well as increase the porosity of the compost (Anand and Apul 2014).

2.2.2. Human waste as fertilizer in history

Human excreta, also known as “night soil”, has been used to improve soil fertility worldwide for a long time. It is especially used to response to agricultural intensification in ancient time. (Kawa et al. 2019) Until the industrialization period, the contamination of drinking water wells led to the modern hydraulic sanitation system. The increasing popularity of flushing toilets has resulted in the increasing water content of night soil, which has lost its value as a fertilizer (Gandy 2004). Expanding cities have also continued to raise the cost of night soil collection (Johnson 2006). As a result, the use of night soil is suspended and human excreta became waste (Kawa et al. 2019). Night soil did not receive renewed attention until the last century. From a sustainability and environmental point of view, recycling of human waste reduces dependence on commercial fertilizers. In particular, it can provide additional micronutrients (Basta 1995). In addition, fertilizers made from night soil are effective in promoting land reclamation (Sopper 1992).

2.2.3. Pros and cons of dry toilets

The main advantage of dry toilets is that they require less water than flush toilets. Modern flushing toilets require 6 liters of water per flush. (Dobson 2022), and an average household uses about 100,000 liters of water a year for flushing. (Stenström et al. 2011). Reducing water use also reduces energy consumption. In developed countries, water resources management is relatively inefficient because a large amount of energy is used to support the production of high-quality water, which in turn is used to flush toilets. (Anand and Apul 2014) In addition, due to the low water requirement of the dry toilet system, it is particularly suitable for arid areas and areas without sewer connections (Berger 2010). On the other hand, composting toilets allow the decentralization (Anand and Apul 2014). Sewage treatment is a sensible topic in rural areas. Connecting rural households to centralized wastewater treatment plants is not justified due to the high cost of connecting pipes. Some households also choose to transport wastewater by truck, which leads to fuel consumption and a higher carbon footprint. Another advantage of composting toilets over decentralized wastewater treatment plants is the nutrient recycling. (Aburto-Medina et al. 2020). After thermophilic biological treatment, human excreta will be degraded and pathogens will be eliminated. “Waste" is no longer waste, but a resource: nitrogen-rich fertilizer.

However, due to lack of knowledge, composting toilets are still not accepted and implemented by the public. (Anand and Apul 2014). There are knowledge gaps in some reviews of dry sanitation systems due to a lack of peer-reviewed literature.

One of the biggest problems with dry pit latrines is the odor. Even with the installation of ventilation ducts, odors are often still detected (Tilley et al. 2014). In addition, composting toilets usually provide a safe end product. However, low temperatures and short residence times can still lead to pathogen residues (Jenkins 2005). Pathogen risks may also occur during the emptying phase if workers are not wearing appropriate protective gear. (Rose and Jiménez Cisneros 2019). Table 2-1 shows a summary of the pros and cons of conventional dry toilets.

Table 2-1 Summary of the advantages and disadvantages of a conventional dry toilet

pros	cons
Reduce household water consumption	Lack of literature and knowledge
Reduce the cost of wastewater treatment	Odors
Possible nutrient recycling	Vectors hard to control
Conformity with ecological design principles	Pathogen risks
Low capital and operating costs	Microbial risks in emptying phase
Decentralized	
Easily built and repaired	
Energy saving	

2.2.4. Development potential and outlook.

Since the 1970s, wastewater treatment research has received more attention than dry pit systems. However, with the growing awareness of resource conservation and waste prevention, and limited water resources caused mainly by the world's growing population, (Aburto-Medina et al. 2020), dry toilets have returned in the public eye and back in the limelight. (Tilley et al. 2014)

In 2021, 3.6 billion people still don’t have access to toilets (United Nations 2022). Poor sanitation spreads disease and threatens their lives. According to the Sustainable Development Goals, the goal is to achieve universal access to sustainable sanitation systems, increase recycling and safe reuse by 2023. However, at the current rate of progress, 2.8 billion people will still lack access to sustainable sanitation systems. (SDG 2022) More must be done to create a world with better sanitation. Composting toilets, as a cheap, low-tech alternative, can be improved and adapted to different regions.

In sub-Saharan Africa, 23 % of the population does not have access to toilets and 31 % do not have a formal sanitation system. (Han and Hashemi 2018). Due to water scarcity in Africa and the lack of suitable pumps, Han's team has come up with an innovative toilet technology for African cities. The main idea of the technology is to use waterless UDDT toilets, which store waste in two different inlets. Microorganisms can also be added to improve the quality of the fertilizer. (Han and Hashemi 2018) In South Asia, 31 % of people still suffer from poor sanitation. (The world bank 2020) According to Sijbesma, developing low-cost models can help to motivate users (Sijbesma 2008). Nowadays, new sanitation alternatives were invented and implemented in South Asia. A low-cost bio-toilet was invented by Arvind Dethe, which changed thousands of lives in India (Bhatia 2019). Composting toilets can also be used on Pacific islands to reduce water consumption and prevent costly water pollution. Humid weather in the tropics produces odors. In order to reduce them, bucking agent needs to be added. However, too much bucking agent is used to cover the waste of other users, which will lead to poor composting conditions. (Leney and Pacific Reef Savers, Ltd. 2017) Therefore, future composting toilets on Pacific islands will need to pay more attention to compost design, odor prevention, and how to ensure that compost contains enough water.

In conclusion, sustainable dry toilets have good prospects for development. The future model should not only meet local climatic conditions, political requirements and public acceptance, but also reinforce the concept of sustainable development, insisting on less water, less energy and better fertilization.

2.3. Composting

2.3.1. Composting process

The composting process is the decomposition of organic matter into water, carbon dioxide and non-degradable materials under aerobic conditions (Rotter, Fritze 2021). Organic content of agricultural and agro-industrial wastes as well as municipal wastes can be used as raw material for composting (Füleky and Benedek 2010) (Sánchez et al. 2017). Generally, it is a biological process that converts organic matter into a more stable form (Sánchez et al. 2017) , with the cooperation of microorganisms and bigger organisms. It may consist of 20 % bacteria, 40 % fungi, actinomycetes, 12 % coelenterates, 5 % other animals, 2 % microfauna and 1 % algae. (Rotter, Fritze 2021). The first stage of composting is the mesophilic phase. Easily degradable substances (e.g. sugars, amino acids and lipids) will first be broken down by bacteria and fungi. Since the aerobic transformation is an exothermic reaction, the temperature rises rapidly from ambient temperature to about 45 °C. (Stentiford and Bertoldi 2010) Then the thermophilic process begins. During this phase, thermophilic microorganisms consume large amounts of oxygen (Help Me Compost 2022) and hydrolyze more complex organic matter (cellulose, hemicellulose, lignin and proteins) (Sánchez et al. 2017). At the same time, a huge amount of energy will be released and the temperature will rise rapidly (Stentiford and Bertoldi 2010). Temperatures can rise up to 70 °C, in which case the pathogens will be destroyed. (Sánchez et al. 2017). The third stage is the cooling stage. In this phase, neutrophilic microorganisms repopulate from surviving microorganisms or external microorganisms. They can break down long polymers (lignin, cellulose, etc.). (Stentiford and Bertoldi 2010) The temperature slowly decreases until it reaches stabilization. The maturation phase is the final and longest lasting phase of composting (Rotter, Fritze 2021). During this period, the fungus works actively in perfect conditions of low temperature, low water content and high oxygen content. After several months of humification process, a stable, dark brown, nutrient-rich product emerges. (Stentiford and Bertoldi 2010)

2.3.2. “zirkulierBAR” project and thermophilic composting plant

"zirkulierBAR" is an interdisciplinary project in Eberswalde that aims to produce a harmless fertilizer from feces through controlled thermophilic composting.

Composting of human feces is carried out by Finizio. Human feces are first collected in a dry toilet, and separated from urine in Barnim. In order to eliminate pathogens, the feces are stored in hygienic containers for seven days at high temperatures and with sufficient oxygen. During this phase, the feces are highly aerated, which accelerates the activity of certain microorganisms and causes the temperature to rise to 70 degrees. This inactivates some pathogens, such as E.coli.(Finizio 2023)

In order to produce high quality humus fertilizer, it is necessary to ensure optimal oxygen supply, regulated moisture and the incorporation of high quality additives such as clay minerals and biochar. Given these requirements, the strategy involves utilizing relatively small windrows. A base width of 2 m and a height of 1 m ensures material stability, and an optimal moisture content of between 55-60 % promotes oxygen circulation within the windrow core.(Finizio 2023)

During the initial composting week, the tumbler delicately processes the approximately 30 meter long compost windrow every day. Its main function is to ensure homogeneous mixing and optimum oxygenation of the material. When the oxygen content in the core of the pile falls below 5 %, the intervention of this machine becomes imperative. Additionally, rolling curtains on the outside of the humus frame provide better protection for the windmill from both wind drying and rain.(Finizio 2023)

The final step is to sieve the humus fertilizer. This step is needed because there are often foreign materials in the fertilizer windrows. The sieve will filter these residues out of the finished substrate. They will be then sent to a waste incineration plant, while the compostable screen residue will be returned to the next batch of windrows. (Finizio 2023)

In addition, the VUNA process is used to produce liquid fertilizers. The first step in the urine treatment plant is to stabilize the nitrogen in the urine in a bioreactor. Then, the trace substances such as drug residues and hormones are removed by means of an activated carbon filter. This results in a regenerated liquid nitrogen fertilizer with high concentrations of all important plant nutrients. (Finizio 2023)

2.3.3. Process factors for composting human excreta

The process factors for human waste composting are similar to those of a regular composting process. However, since human feces contains pathogens, sanitation and elimination of pathogens are the most important considerations in the composting process.

The C/N ratio of human excreta is around 8, which is much lower than the suggested initial C/N for composting. Therefore, carbon rich bulking agents (e.g. sawdust, dried leaves etc.) needs be used to adjust the ratio (Frederick C. Miller and F. Blaine Metting 1992).

It is observed that the water content in urine and feces is higher than most biowaste: 82 % in feces (ZAVALA LOPEZ et al. 2002), 76 % in food waste (Krogmann 1994), 64-77 % in downtown biowaste (Woyczechowski et al. 1995), 18-20 % in paper (Rynk et al. 1992).

High moisture helps microorganisms to absorb nutrients, but too much moisture can lead to the creation of an anaerobic environment. Therefore excess water needs to be removed from feces compost. (Anand and Apul 2014) (Aburto-Medina et al. 2020)

Optimal oxygen concentration is suggested between 15 % and 20 % (Frederick C. Miller and F. Blaine Metting 1992). When ensuring sufficient oxygen, the amount of exceed air should be controlled, because too much exceed air will lower the moisture content (Anand and Apul 2014).

Sanitation and pathogen control are considered indicators of composting toilet safety. Pathogens can be effectively reduced to safe levels at specific temperatures and residence times. Requirements for pathogen elimination vary from region to region. And according to Anand and Apul, thermophilic composting should be performed at 55 °C for two weeks or 60 °C for one week (Anand and Apul 2014). The World Health Organization recommends composting at 55 °C-60 °C for one month followed by maturation for 2-4 months to ensure satisfactory reduction of pathogens. However, composting pits in composting toilets are usually small, resulting in ineffective temperature increases (Jenkins 2005). Therefore, to ensure the elimination of pathogens, secondary composting can be conducted with regular turning. Other options (long storage, UV disinfection etc.) can also be chosen according to the economic and geological conditions. (Anand and Apul 2014) At last, indicator microorganisms such as fecal coliform and fecal streptococcus must be tested and the results should be below the limit values before they can be returned for reuse. (Krogmann et al. 2010)

2.3.4. Emissions

Even though composting is considered as an environmental-friendly process, a badly conducted compost will cause air and leachate emissions (Sayara and Sánchez 2021). Leachate generation depends on the system type and feedstocks. Generally, the water content in compost comes from the origin water in feedstock, water generated by microorganisms. Besides, in an open system, rainwater is another source of moisture (Boldrin et al. 2010). At the same time, water leaves the system through evaporation, which is influenced by air and compost temperature. When water continues to accumulate, leachate is produced, posing a threat to groundwater. In conclusion, in order to control the release of leachate, it is necessary to separate the soil from the compost by laying polymer or to have enclosed composting. (Boldrin et al. 2010). Figure 2-4 shows the water balance and gas emission from compost.

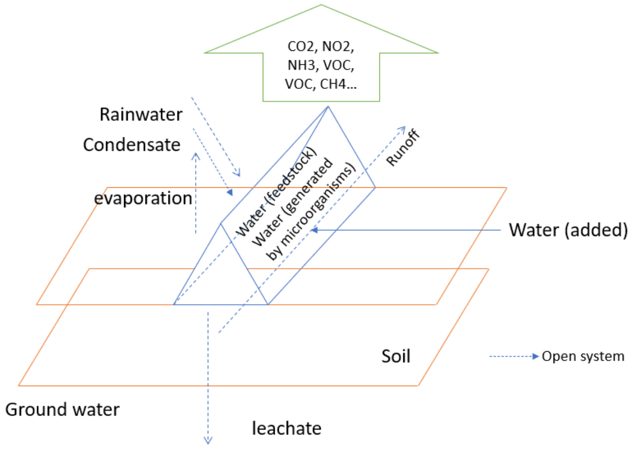


Figure 2-4 water balance and gas emission from compost

Another problem is the gas emission. The main component in the exhaust air is CO_2 (0-50 %). CO_2 emission from composting is not considered as an attribution to global warming as its carbon source is biogenic. However, CH_4 and NO_2 which are produced particularly due to lack of oxygen, are also present in the exhaust gases. Their global warming potential is 25 and 298 times higher than CO_2 respectively (IPCC 2007). NH_3 is another odor-effecting gas that can be found commonly in exhaust air. The presence of NH_3represents the loss of nutrients. All the composting facilities or sites should reduce the gas production by ensuring sufficient oxygen and adjust C/N ratio of the initial feedstock while avoiding gas emission by installing a biofilter (Boldrin et al. 2010).

3. Materials and method

To achieve a comprehensive overview of various flow interactions and nitrogen dynamics between the municipal and agricultural sectors in the Barnim region, it is crucial to clarify the interactions, especially the impact of municipal activities on agriculture. The use of Material Flow Analysis (MFA) and Substance Flow Analysis (SFA) has proven to be effective in providing an in-depth visualization and comprehensive overview of these interactions. In this study, changes in material and nitrogen content were investigated in a real life situation.

Time comparisons are primarily based on 2016 and 2020 data. The assessment aimed to understand the change in the baseline scenario for material and nitrogen content in these two years, taking into account various assumptions. Following the baseline analysis, scenario studies were initiated to further explore the potential. Specifically, three scenario studies were developed: a theoretical scenario, a technical scenario, and a future sustainable scenario. The purpose behind these scenarios was to determine the potential of nitrogen recovery rate under different conditions and to measure its importance relative to the total fertilizer inputs required for crop production. To assist in this complex analysis, the software tool STAN 2.6 was employed, designed to proficiently balance both material and substance flows (Cencic and Rechberger 2008).

3.1. Model description

3.1.1. Model for baseline scenario 2016 and 2020

The baseline scenarios are based on statistical data, supplemented by reasonable assumptions related to Barnim, and seek to provide a comprehensive picture of biomaterial flows and nitrogen levels in 2016 and 2020. For both years, the same models with minor differences were used, view chapter 3.3.1 (flow B4). As shown in Figure 3-1, these models consist of four main blocks: household (blue), agriculture (green), waste management (grey), and food production (yellow). The main focus of the study is the nitrogen stock in the soil of the crop production sector. A comprehensive model figure delineating all the flows in greater detail is available in Appendix B.

In the household section, the focus is primarily on human metabolism and daily life. This includes food and water intake, household food waste production, and urine and feces generation. As for waste management, it includes two key components: the treatment of biowaste generated by the organic fraction of municipal solid waste (OFMSW), and processes related to wastewater treatment and sewage sludge treatment. The food production component centers on achieving balance - considering the raw inputs to food production, human consumption behavior, and the resulting food wastes. In the end, the agriculture section is further divided into different processes: farm animal husbandry, crop production and intercropping. This block also includes the crop product produced, animal products from farm, straw yields as well as forage demand. For the crop production, stock changes within the year were quantified and it was assumed that no more stocks would be present in the baseline scenario.

As a result, the model consists of 4 main blocks, 14 processes and 59 individual flows to describe the different agricultural and municipal related processes. The summary of the flow can be found in Appendix C. .

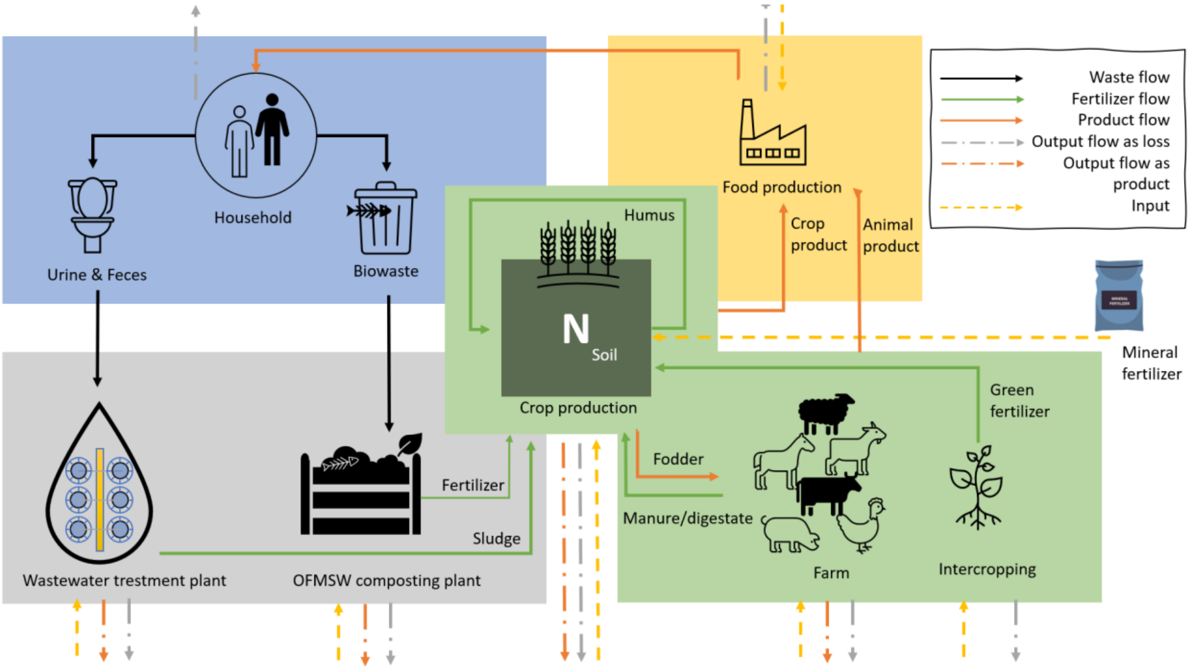


Figure 3-1 A simplified model schema with four main blocks (human, agricultural, waste management and food production)

3.1.2. Urine and feces recycling model in scenario study

The modeling for the scenario study expands on the 2020 baseline scenario. One notable addition is the "Recycling Block," which includes a dry toilet system for urine and feces separate collection, a urine treatment unit, and a feces thermophilic composting unit. The block primarily receives feces and urine from residents. The input of feces and urine varies depending on the different scenarios. Supplementary materials such as green waste and clay materials are also incorporated into the process. The main outputs of the recycling unit are liquid fertilizer extracted from urine and humus fertilizer from feces composting. Figure 3-2 is a flow chart illustrating the recycling process of human waste from collection to product.

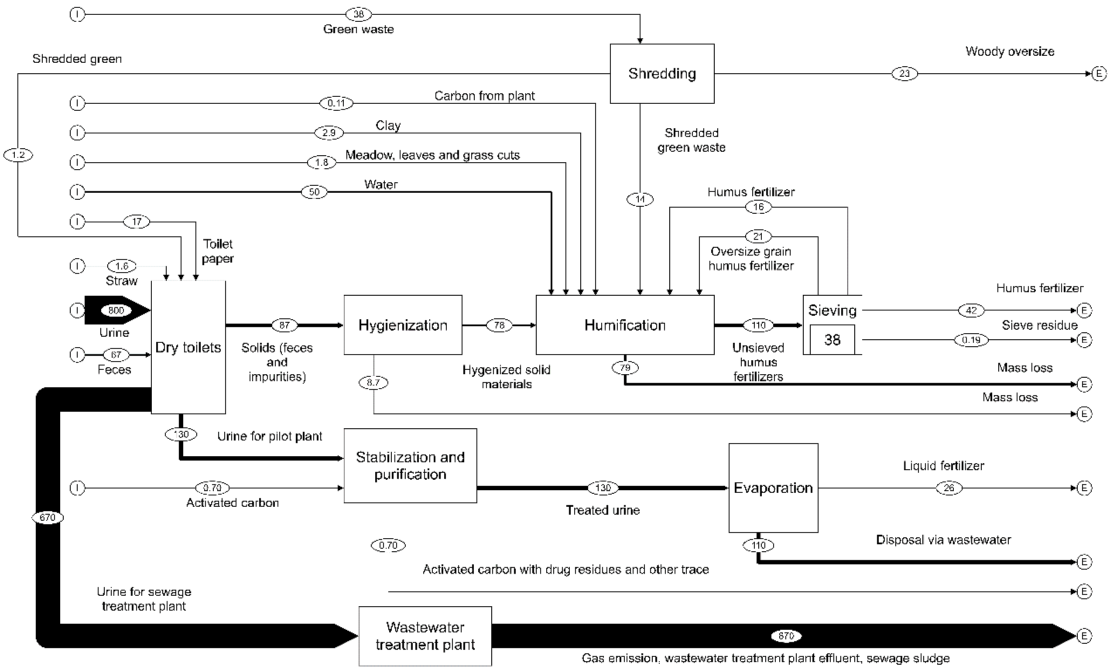


Figure 3-2 Flow chart of the urine and feces recycling process (dry toilet collection, urine treatment and thermophilic composting)

The value of flows are derived from the experimental data collected in the zirkulierBAR project in 2020.

3.1.3. System boundary

The system boundary of this model emphasizes two main areas: the metabolism of the residents (food intake and digestion) and agriculture. In the agricultural domain, all primary materials that are inextricably linked to the agricultural production process are taken into account. However, ancillary materials and processes that support the production and operation of farms and crops are excluded (e.g., vaccines for animals, mechanical tools, etc.). The primary perspective of the analysis is nutrient- and product-based flows, discarding secondary or peripheral elements.

In the area of human metabolism (food absorption and digestion) and subsistence, the modeling focuses on activities related to food intake and subsistence. It is worth noting that while green waste and municipal wastewater are important considerations for human activities, they are delineated as input streams to a system and therefore exist outside of the system boundaries. This is because green waste originates from parks and gardens and is not relevant to human metabolism. Municipal wastewater, on the other hand, is a sum of rainwater, external water, and greywater used by residents for domestic purposes (e.g., Washing dishes, bathing, and similar activities do not involve blackwater, which is water contaminated with fecal matter)

To further clarify the concept of "inputs", these flows include substances that flow into the Barnim area from other areas, substances extracted from the atmosphere and the environment, and also substances that are necessary for certain processes but are not directly related to agriculture or residential life.

In contrast, "outputs" include all entities leaving the Barnim area, such as goods exported, losses from system processes, and fertilizers not utilized by agriculture.

This defined system boundary ensures a structured analysis of the material flows within the Barnim area, detailing which flows are part of the system, which are considered peripheral, and which are not considered.

3.2. Scenario study explanation

The scenario studies were conducted in three different scenarios in order to gain a clearer perspective on the feasibility and potential of using recycled fertilizers generated from composting of human waste. These scenarios are referred to as the theoretical scenario, the technical scenario and the future sustainable scenario.

In the theoretical scenario, it is assumed that all urine and feces generated by the residents of Barnim are collected through dry toilets and then processed and recycled. One of the benefits of this approach is the elimination of water used for toilet flushing. According to (urbansky 2015), water used for toilet flushing accounts for approximately 31 % of total water consumption. This translates to an annual water savings of 14.4 m^3 per person, which would be removed from the wastewater. In order to avoid odor production, a portion of green waste and straw are used as input materials. Thus, smaller quantities of green waste will be diverted to make fertilizer from the organic fraction of municipal solid waste (OFMSW).

In the technical scenario, the main difference lies in the quantity of input material of the composting plant. Here, it is assumed that only people in rural areas have the economic and technical feasibility of installing dry toilets in their homes. Therefore, composting plants only process urine and feces from households connected to collection pits and small-scale wastewater treatment plants.

The future scenario projects a sustainable framework for 2030. A prominent expectation is population growth over the next decade. In addition, guided by changes in regulation, the sewage sludge regulation specifies that by 2029, wastewater treatment plants (WWTPs) serving more than 100,000 inhabitants must recover phosphorus according to a cutoff value of 20 grams of phosphorus per kilogram of dry matter, as shown in Sewage Sludge Ordinance

(AbfKlärV) . Therefore, it is expected that only sewage sludge from WWTPs serving less than 100,000 inhabitants will be returned to agricultural practices. In rural areas, changes in water management are expected. It is expected that graywater from household activities will be treated through filtration systems and reintegrated into household use. This suggests that there will be a significant reduction in domestic wastewater that relies exclusively on collection pits.

Table 3-1 A summary of the scenario-specific assumptions and resulting flow variations of three scenarios

	Theoretical scenario	**Technical scenario**	**Future sustainable scenario**
Year	2020	2020	2030
Source of human waste for recycled fertilizer	All residents	Residents with connection to small scale WWTPs and collection pits	Residents with connection to small scale WWTPs and collection pits
Population	-	-	+5 %
Human waste	-	-	+5 %
Municipal Wastewater generation	Toilet flushing water excluded (all residents)	Toilet flushing water excluded (for small-scale WWTPs and collection pits)	Toilet flushing water excluded (small-scale WWTPs) All municipal WW from collection pits excluded
Sewage sludge as fertilizer for agriculture	Based on the baseline scenario 2020	Based on the baseline scenario 2020	SS from WWTPs with a capacity <100,000 cap
Livestock	-	-	Cattle -10 %
Food waste	-	-	- 43 %
Imported food: local food consumption	1:1	1:1	1:3
Crop based protein: Animal based protein	1.5:1	1.5:1	1.25:1

Furthermore, In Germany, a shift towards reduced consumption, particularly of meat, is becoming apparent, as highlighted by (Logan 2023) . Considering this trend, future scenarios anticipate fewer cattle being raised on farms and less reliance on meat proteins in the daily human diet. Another sustainable trend is the preference for local food over imported food, which can significantly reduce transportation-related greenhouse gas emissions. As a result, consumption of locally produced food is expected to increase by 2030. In addition, advances in sustainability are expected to reduce food waste in the supply chain and at the household level. According to (Schmidt et al. 2015) , of the 75.2 kg of food per capita in Germany, 32.9 kg could theoretically be avoided. Therefore, this study hypothesizes a reduction in food waste of approximately 43 %.

In terms of recycled fertilizers, it is assumed that only urine and feces from rural areas (especially those using collection pits and small-scale WWTPs) will be collected separately. These materials would be processed through thermophilic composting and then reused in agriculture, thus completing the nutrient cycle. Table 3-1 shows the comparison of the three scenarios and a summary of the impacted flows.

3.3. Flow description and data acquisition

3.3.1. Household

As shown in Figure 3-3, the principal processes in "Household" are human metabolism and the household food waste generation. The focus of the block is to highlight the balance and interaction between human food consumption and the subsequent generation of waste through metabolic processes and discarded food.

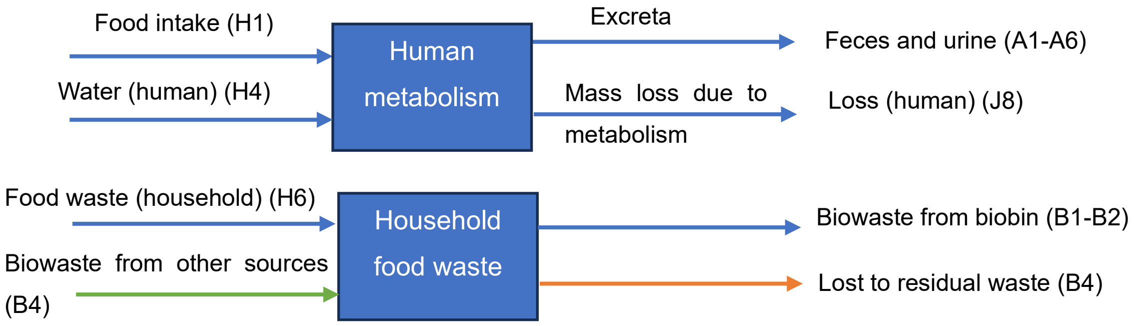


Figure 3-3 Flows and processes in the block "household"

Flow A1-A6: feces and urine

The generation of feces and urine in Barnim is derived from universal daily excretion rates. The nitrogen content for both urine and feces are then deduced from daily nitrogen excretion rates per individual. The division of fecal and urine waste is categorized by the origin of connection: central wastewater treatment plants (WWTPs), small-scale WWTPs (serving fewer than 50 residents (Landkreis Barnim 2023)), and collection pits. Most of these excretions undergo treatment at central WWTPs, whereas a smaller proportion is processed at small-scale WWTPs. Wastewater collected in collection pits is temporarily held before being transported for treatment at the central WWTPs.

Flow B1-B2: Biowaste flows from biobin

Data on the quantity of biowaste generated from households in the Barnim region can be directly obtained from Statistics Office Berlin Brandenburg. The characteristics of biowaste may vary between rural and urban areas, as highlighted in a study conducted (Sailer et al. 2021). To determine whether a specific area falls under the urban or rural category, the distinction is made based on population density.

In the Barnim region, the average population density, calculated as the ratio of population to area, was 121 in 2016 and 127 in 2020. To identify rural areas, the population density of each Gemeinde (municipality) is calculated. Any Gemeinde (municipality) with a population density lower than the average for the entire Barnim region is considered rural. Additionally, all Gemeinde (municipality) designated as "Stadt" (city) are classified as urban areas, regardless of their population density.

The nitrogen content in biowaste from bio-bins is determined by multiplying the biowaste generation quantity with its respective nitrogen concentration. The proportion of urban and rural residents in Barnim as well as the characteristic of biowaste from biobin in urban and rural areas are shown in Table (appendix) A-2 and Table (appendix) A-3.

Flow H1, H4, H6: Food intake, water consumption and Food waste (household)

Food consumption is estimated from literature findings on adult food intake in Germany. Drinking water is derived from the average daily consumption figures. Nitrogen flow stems from the average protein intake in Germany, which is then converted to its nitrogen content. It's assumed that the consumed water contains no nitrogen. (Further references can be found in Table (appendix) A-1). In addition, the calculation of food waste (household) (H6) can be found in chapter 3.3.4.

Flow B4: Biowaste from other source and loss to the other waste fraction (B4)

In the model for 2016, the amount of household food waste exceeds the amount of biowaste collected in the biobin. This suggests that some of the food waste was diverted to other waste streams. In contrast, in the model 2020, the amount of biowaste collected in biobin surpasses the amount of household food waste. This discrepancy suggests that biowaste from other sources may have been mixed into the biobin, necessitating additional input flows. This difference in inputs and outputs between biowaste and household food waste is the only minor difference between the 2016 and 2020 scenarios.

Flow J8: Loss (human)

Human metabolic loss is the loss of mass during the body's metabolism and activity. The value of this flow is automatically calculated by STAN.

3.3.2. Agriculture

Block: Crop production

Agriculture is a very complex and multifaceted subject. Firstly, the crop production system will be illustrated and discussed. The input and output flows of crop production are shown in Figure 3-4.

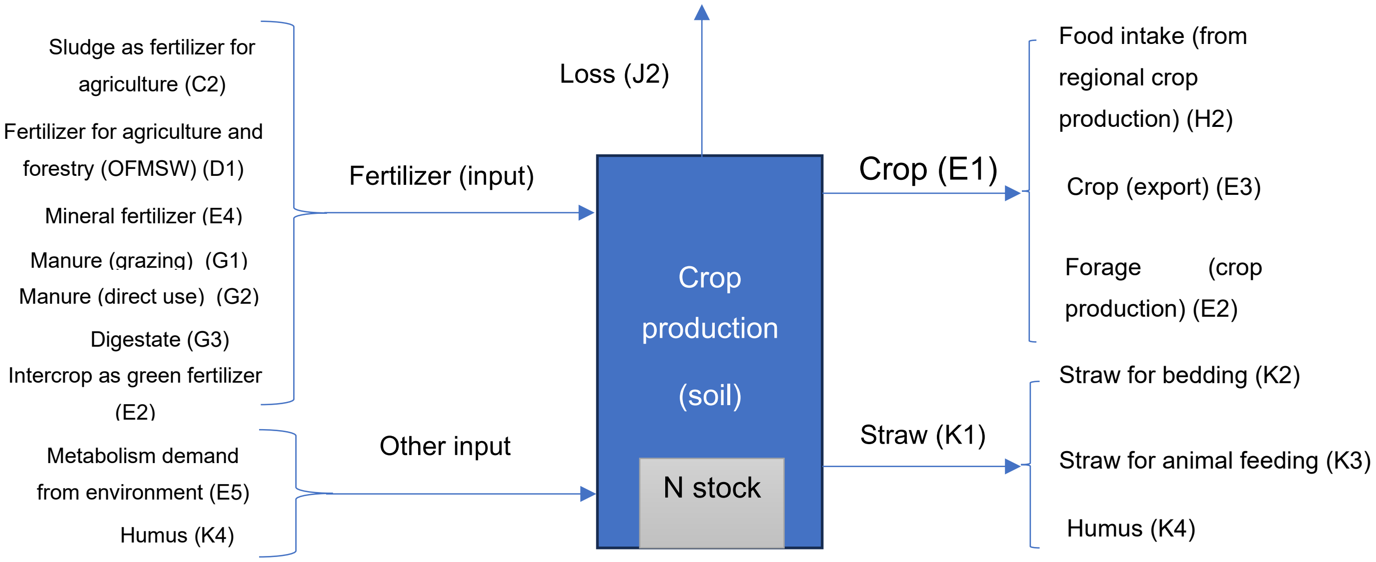


Figure 3-4 Flows and processes in the block "Agriculture"

Input flows during crop production are mainly fertilizers from different sources, elements taken up by plants from the atmosphere and the environment (E5), and straw brought back to crop production to protect the humus balance (K4) (Weiser et al. 2014). In this study, nitrogen and mass taken up by plants from the soil are not considered in K4 because crop production process also includes topsoil. In addition, fertilizer inputs included organic fraction of municipal solid waste (OFMSW) treated bio-waste fertilizer (D1), sewage sludge (C2), manure left on the pasture during grazing (G1), directly applied manure (G2), digestate (G3), and intercrop green manure (E2). In the scenario study, liquid fertilizer (T3) and humus fertilizer (T21) were also associated with crop production.

The outputs of crop production were mainly crop products (E1), by-products (straw) (K1) and fertilizer application losses (J2). In the case of crop products, some of the products will be consumed by the local people in Barnim (H2) or exported to other areas (E3), while the rest will be used as animal feed on farms (E2). Straw is a by-product of crop production and plays a vital role in the cycle. Economically feasible harvested straw is used as animal bedding (K2) or animal feed (K3). Some of the straw is left in the field to maintain the humus balance of the land (K4).

Flow E1, E2, H2: Crop Product

The data pertaining to crop production is sourced from statistical office Berlin Brandenburg, encompassing information on 20 distinct crop types. The aggregate crop production is derived from the summation of these 20 crops' outputs.

The harvested crop is allocated for local food consumption in Barnim (H2), exported to other regions (H3), and utilized as animal forage (E2). Owing to data limitations, fodder from crop production is determined based on an estimated percentage (see assumption chapter 3.4).

The nitrogen composition of each crop is delineated in the Fertilizer ordinance (DüV). The cumulative nitrogen present in the crop is deduced by multiplying the respective crop yield with its corresponding nitrogen concentration.

Flow K1-K4: Straw

In practical terms, the straw from wheat, rye, triticale, barley, and oats is predominantly considered. The theoretical production rate of straw can be ascertained by multiplying the crop-residue-ratio with the associated yield. Yet, due to machinery constraints, only straw of a particular height can be effectively harvested and collected (Brosowski et al. 2020). The empirical collection rate is computed utilizing a collection ratio, which is derived from the stubble height, growth height, and the feasible collection ratio. This feasible collection ratio is quantified as the difference between the average grown height of diverse crops and the stubble height, divided by the average growth height (see Table (appendix) A-5). According to (Weiser et al. 2014), straw for animal bedding is another technical constraint.

The determination of straw utilized for animal bedding in the Barnim region is premised upon the population of various animal species. Initially, the requisite straw for animal bedding can be quantified using Equation 3-1, as outlined in (Brosowski et al. 2020). In this context, Brosowski has meticulously documented values for Gp, Gd, Hm, and Ba for ten distinct animal groups pertinent to the Brandenburg region.

$$S_i = \sum (A_n - (A_n \times G_p \times G_d)) \times H_{sm} \times B_a \tag{3-1}$$

S_i	straw used as bedding (Tg fm a−1);
A_n	number of animals;
G_p	share of grazing animals (%);
G_d	duration of grazing period per year (%);
H_{sm}	share of animals in straw based housing systems (%)
B_a	Bedding requirements (Mg/a) for every livestock subcategory.

To make an accurate assessment using this equation, animals must be counted accurately. Data from Statistical Office Berlin Brandenburg counts the number of cattle, pigs, sheep, goats and chickens in the region. While aggregate data are available for geese, ducks, and turkeys, individual counts of these animals are lacking. In order to fill this data gap, the distribution proportions of each of these poultry species counted in Brandenburg were used to project their numbers in Barnim. Conclusively, by aggregating the straw bedding needs for each animal category, the cumulative straw consumption for animal bedding in Barnim is determined.

In Germany, the collected straw cannot all be used for other purposes (animal feeding or sustainable use) regarding the humus balance. This is essential for maintaining soil health and mitigating continuous humus depletion due to annual cultivation and harvesting practices. The quantity of straw required to maintain the humus balance is contingent upon regional soil conditions. (Weiser et al. 2014) studies different potential for straw utilization. It is also illustrated that Barnim boasts a positive humus balance, which is more between 100-300 kg humus C/ ha arable land/ year, signifying that crops can be harvested for other usages. He also declaims that, in order to avoid overestimating the sustainable potential, the amount of straw not required for the specified humus balance is reduced by 10 % (Weiser et al. 2014). Since Barnim is positive in humus, it can be assumed that at least 10 % of the technical potential is used for humus balance in Barnim.

After supplying the straw in animal bedding and humus reintroduction, the straw can be used as forage for animal feeding (Figure 3-5). Moreover, the utilization of straw is also affected by the radius of the collection distance, which dictates its financial viability (Ma et al. 2022). Nonetheless, this aspect is not incorporated into this study due to the absence of pertinent information.

The nitrogen content for straw is also listed in the fertilizer ordinance (DüV). The total amount of nitrogen in the straw is determined by multiplying the amount of straw with its specific nitrogen content.

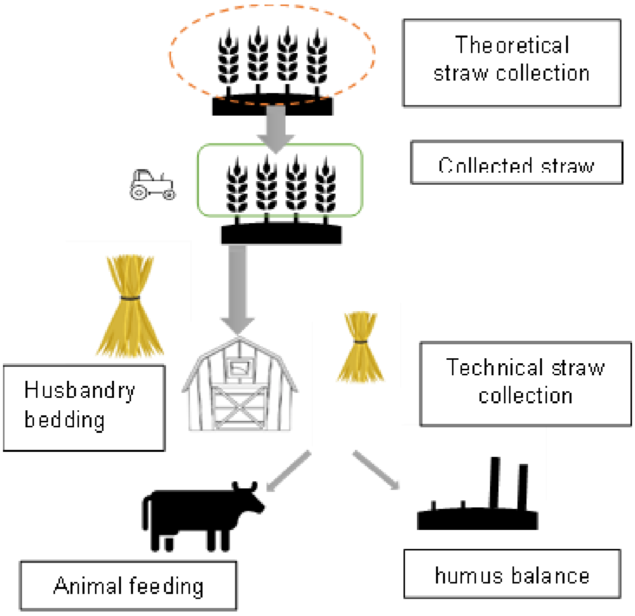


Figure 3-5 Illustration of straw collection potential and usage based on (Weiser et al. 2014)

Flow E5: Metabolism demand from environment

To streamline the understanding of crop growth processes, a simplified equation focusing on plant metabolism was chosen. A large portion of plant weight gain is attributed to carbon (Maclean et al. 2010). In this study, it is assumed that all carbon absorbed by plants comes from the atmosphere. This uptake can be quantified by Net Primary Productivity (NPP), which represents the amount of carbon absorbed by a plant in a given time period (Chapin and Eviner 2007). Detailed NPP values for various crops are given in Table (appendix) A-6.

Water is another key element for crop growth. This study focuses only on the net water input, i.e., the actual water content of the crop. Since the soil maintains a constant water storage capacity in a long period of time, external factors such as irrigation and rainfall are not directly accounted for, but are assumed to be lost through runoff or evaporation.

Moreover, nitrogen plays a crucial role as an input element. It can be introduced through rainwater or be fixed directly by leguminous plants. Additionally, nitrogen is supplied with seeds and planting materials. References and literature that support these calculations are available in the Table (appendix) A-4.

Flow E4: Mineral fertilizer

Based on data from the Brandenburg statistics office regarding nitrogen fertilizer purchases, it's inferred that the acquired fertilizers are utilized in agriculture. The amount of inorganic fertilizer used in Barnim is then extrapolated from Brandenburg figures, considering the proportion of cultivation area.

Flow J2: Loss

Nitrogen loss in agriculture comes mainly from the application of different fertilizers. This nitrogen is released in the form of N_2O, N_2, NH_3, etc. and is also lost through leaching and runoff. Measuring the whole process of material loss can be very complex. In this study, nitrogen is assumed to account for half of the overall gaseous losses. Nitrogen emission rates for different fertilizers are detailed in the Table (appendix) A-7.

Block: Farm (Livestock)

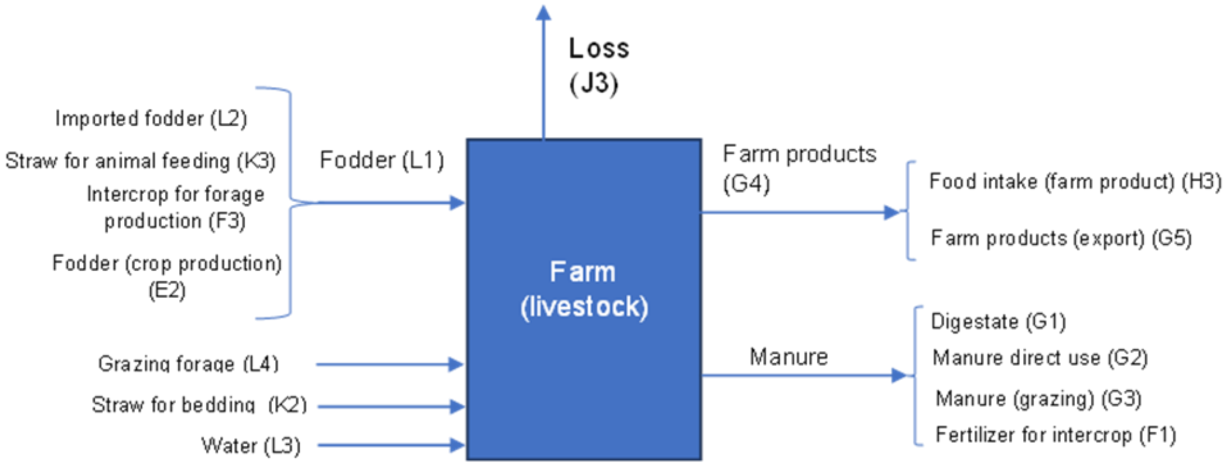


Figure 3-6 Flows and processes in the block "Farm"

As shown in Figure 3-6, livestock systems present a multifaceted range of comprehensiveness. For livestock management, the main inputs include straw for bedding (K2), water intake (L3), forage consumed in grazing activities (K2) and fodder provided (L1). The total fodder demand (L1) includes fodder imported from other regions (L2), fodder cultivated within the region (E2), and intercrops purposed for forage (F3). Outputs from the agricultural practices encompass farm products (G4), categorized into animal products tailored for the Barnim region (H3) and those earmarked for export (G5). In addition, manure is also an important output from farm: that which is directly deposited on fields due to grazing (G3), directly utilized manure (G2), and digestate (G1). The utilization of manure in agricultural practices is split between crop production and intercropping. It is assumed that the amount of manure allocated to regular crop cultivation is determined by subtracting the amount needed for fertilizing intercrops from the total manure produced (Table (appendix) A-8).

Flow L1-L3, E2,: Fodder and water consumption

Forage demand is assumed by the feeding demand and raw protein demand of each type of animals. The water consumption is also estimated by the average water demand among an animal group. The chosen data and the reference can be found in Table (appendix) A-9.

Imported fodder and regional produced fodder calculation is based on the assumption (chapter 3.4) .

Flow G1-G3: Manure

The form of manure varies depending on its water content. Specifically, for cattle and pigs, manure can be classified as either slurry (Gülle) / liquid manure (Jauche) or farmyard manure (Stallmist). (poultry's excreta is called poultry dry manure (HTK in German), and it's considered in the same group as the farmyard manure.) This distinction arises due to the varied methods of manure collection. In the case of slurry (Gülle) / liquid manure (Jauche), animal excreta are stored in liquid form without distinct ingredients. Conversely, for farmyard manure (Stallmist), excreta are combined with bedding, primarily straw, resulting in a solid form after the surplus urine is drained.

The table "Berechnung Lagerraum und Nährstoffanfall für tierhaltende Betriebe mit Fläche" (Calculation of storage space and nutrient accumulation for livestock farms with area) from (LfL 2023) can be used to estimate the amount of raw slurry (Gülle), liquid manure (Jauche), and farmyard manure (Stallmist) produced. By analyzing the estimated manure production in Barnim and Brandenburg, the proportions of regional manure production can be analyzed. Then, using the statistical data on manure as fertilizer based on the state of Brandenburg, the direct use of manure and digestate in the Barnim region is calculated in proportion of the estimated data. Furthermore, using this table, the manure produced during grazing and its nitrogen content can be calculated directly.

This comprehensive calculation of the generation of raw slurry (Gülle) / liquid manure (Jauche) or farmyard manure (Stallmist) generation considers several factors:

- The proportion of liquid manure to farmyard manure (solid manure), contingent upon their husbandry method.
- Volume of bedding used (Einstreumenge).
- Seasonal grazing rates, differentiated between April to September and October to March (Table (appendix) A-10).
- The count of various animal types.

Flow L4: Grazing forage

The forage consumed during grazing sessions is termed as "grazing forage". Calculation of ingested nitrogen content is obtained by multiplying the nitrogen in excreta by the digestion factor (Lantinga et al. 1987). The grazing material flow is further modified according to the nitrogen content of the grazed forage.

Flow J3: Loss

The loss in agriculture is calculated based on the balance by STAN.

Flow G4, G5, H3: Farm product

Total farm production is a combination of meat, egg and milk production. Specifically, meat slaughter production and egg production are extrapolated from the animal population share of Brandenburg. Milk production, on the other hand, is derived by multiplying the number of dairy cows with the average milk production efficiency of the Land Brandenburg. The consumption of the animal products are estimated based on the assumption (chapter 3.4) .

Block: Intercrop

Flow F2, F3: Intercrop production

Intercropping refers to the practice of planting a secondary crop during the intervals between the main crop's harvest seasons (Asseng et al. 2014). A primary benefit of intercropping is its ability to mitigate issues such as nitrogen leaching, nitrogen accumulation, nutrient and soil breakdown, improved root penetration, carbon and humus enrichment, and providing protein to nourish the soil biota due to nitrogen (FiBL 2013). Once matured, the intercrop can either be left on the field, serving as green fertilizer, or harvested for forage production.

The cultivated area of intercrops is assessed separately for green fertilizer and for forage purposes. Data is sourced from statistical office Berlin Brandenburg and is updated every four years. The annual intercrop cropped area is calculated by summing the areas from both the winter and summer seasons. However, for the years 2015-2016 and 2019-2020, while total figures for summer intercrop cultivated area are available, a specific breakdown for green fertilizer and forage is absent. To address this gap, winter data was utilized to determine the ratio of green fertilizer to forage cropped area, and this ratio was then applied to estimate the summer cultivated area for each category. The yield of intercrop and its corresponding nitrogen content are shown Table (appendix) A-12.

Flow F1: Intercrop fertilizer demand

Based on the report by (LfL 2013) , intercrops also necessitate fertilization. A representative average fertilizer demand was selected to ascertain the nitrogen requirement for intercrop cultivation (Table (appendix) A-12). Given that intercrops are not cash crops, it is assumed that the requisite fertilizer would not be procured from external regions. Instead, it is assumed that all fertilizers are sourced locally, predominantly from regional farm-produced fertilizers.

Flow F4: Environmental metabolic demand is calculated in the same way as the metabolic demand for crop production Table (appendix) A-4 .

3.3.3. Waste management

Block: OFMSW biowaste treatment

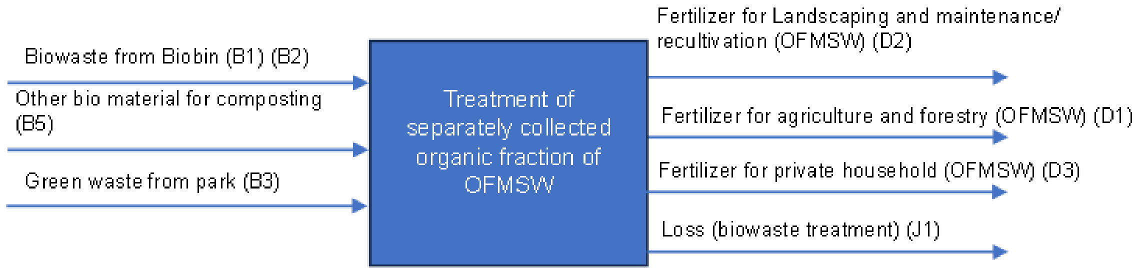


Figure 3-7 Flows and processes in the block "OFMSW biowaste treatment"

As shown in Figure 3-7, the organic fraction of OFMSW encompasses biowaste from the biobin (B1-B2) and green waste collected from parks (B3) and other bio material for composting (B5). Biowaste generation in urban and rural areas has been previously detailed in an earlier section. Data on green waste generation is directly sourced from statistical office Berlin Brandenburg. The primary product from treating the organic fraction is fertilizer. This fertilizer serves landscaping and maintenance or recultivation purposes (D2), agriculture and forestry (D1) and also available for private household use (D3). The loss (J1) stands for the loss during the treatment process and is determined based on the mass balance.

Based on the waste balance in Barnim, the total amount of waste being composted is larger than the sum of biowaste from biobin and green waste. Thus, it is assumed the rest is from the other bio material for composting. The detailed source of this biowaste is not known. Furthermore, the information of biological treatment and utilization of produced compost is only available at the Brandenburg level due to data protection regulations. To estimate the quantity of compost fertilizer used in Barnim, values are derived using the proportion of the population in Barnim relative to the entire population of Brandenburg. Furthermore, the nitrogen composition of the compost was chosen to be 0.7 % (referenced from (Cuhls et al. 2015)).

Block: Wastewater treatment

In the Barnim region, the wastewater treatment process involves the treatment of urine and feces at wastewater treatment plants (WWTPs). This includes the disposal of wastewater through the sewer system to the WWTPs and the collection of waste from mobile collection pits, which is then transported to the WWTPs for treatment. Data from the "Kommunale

Abwasserbeseitigung im Land Brandenburg_Lagebericht (Municipal wastewater disposal in the state of Brandenburg_Management report) 2019" and "2015" reports were utilized to calculate the respective shares of the population in each Gemeinde (municipality) connected to the central WWTPs, collection pits, and small-scale WWTPs. These shares were used to estimate the wastewater treatment situation in 2016 (by multiplying the 2015 share by the population in 2016) and in 2020 (by multiplying the 2019 share by the population in 2020).

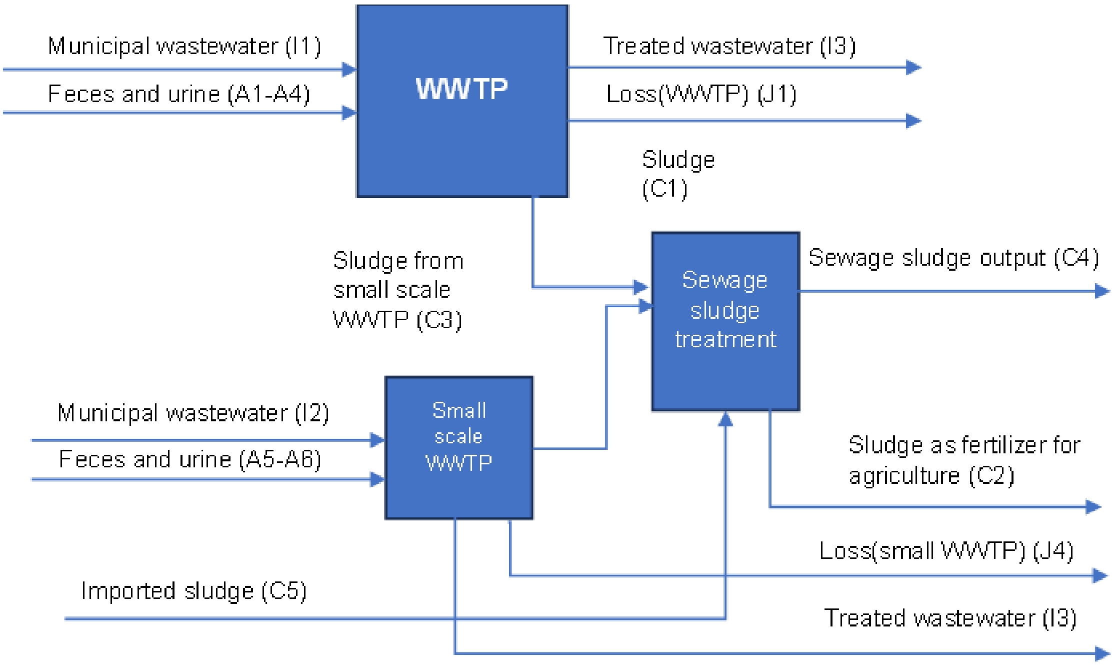


Figure 3-8 Flows and processes in the block "Wastewater treatment"

In the wastewater treatment system (Figure 3-8), waste products (feces and urine) from residents connected to the central wastewater treatment plant (WWTP) are combined and processed with municipal wastewater. For residents not connected to the central WWTP, their wastewater is initially stored on-site before being transported to the central WWTP for processing. Meanwhile, wastewater from smaller community groups is addressed by small-scale wastewater treatment plants. The end products of these treatment processes are treated wastewater and sludge. The sludge from both centralized and small-scale treatment plants is combined, and it may serve as fertilizer for agriculture (C2). However, the majority of the sewage sludge undergoes thermal treatment.

Flow I1-I4: Municipal wastewater input and treated wastewater output

Wastewater generation is obtained from statistical office Berlin Brandenburg. This data encompasses household wastewater, rainwater, and external water. Given that the only available data points are for 2016 and 2019, the 2020 figures are inferred using the external water and rainwater inputs from 2019. Additionally, to bridge the data gap, an average household wastewater generation rate is computed. This assists in estimating wastewater volumes for the various wastewater treatment connections.

The nitrogen content in wastewater is referenced from (DWA 2011). It indicates that raw wastewater typically holds about 73 mg/l of nitrogen. Post biological carbon elimination, this value drops to around 50 mg/l, and with further nitrogen elimination, it can go as low as 13 mg/l. A majority of Barnim's WWTPs employs the denitrification process for nitrogen removal (DWA 2011) . However, according to the wastewater ordinance (AbwV.), smaller WWTPs are not regulated for nitrogen content in treated wastewater due to limited capacity. As a result, it's presumed in this study that small-scale WWTPs lack an advanced nitrogen elimination process. Accordingly, the nitrogen content in the effluent from standard and small-scale WWTPs is set at 13 mg/l and 50mg/l, respectively. It's also worth noting that, based on (Ekama et al. 2011), the volume of treated wastewater is projected to be 97 % of the initial input volume.

Flow J1,J4: Loss

The loss from WWTPs are the elimination of the pollutants through the gaseous phase. It is calculated based on the mass balance.

Flow C1-C4: Sewage sludge

The production of sewage sludge from both WWTP and small-scale WWTP is extrapolated in line with their respective wastewater input ratios. Furthermore, statistical office Berlin Brandenburg provides data related to the imported, exported and disposed sewage sludge, as well as its various utilization routes based on Barnim region. Regrettably, there's a data gap for 2016. Thus, the 2017 data from Barnim was utilized for calculating sewage sludge output, given the consistent figures from Brandenburg during this period. For nitrogen calculations, an average value derived from a compilation of literature sources was selected (Table (appendix) A-14).

3.3.4. Food production

The total input to food process in Barnim region is determined by the combination of regional food consumption and imported food consumption (Figure 3-9).

Figure 3-9 Flows and processes in the block "Food production"

Flow H2, H3, H5: Food input

The calculation of regional and imported food consumption is determined by estimated shares. Based on data from (FAO 2023), the mean protein intake from animal sources is approximately 63 g/cap/d, compared to about 42 g/cap/d derived from plants. Consequently, the estimated nitrogen flux from regional farm is in a ratio of 1.5:1 compared to crop products. In addition, within regional food, it is subdivided into crops and products from local farms. This is also derived through estimation due to lack of data.

Flow H6, J6: Food waste

According to (Schmidt et al. 2019), food waste generation in Germany stands at 75.2 kg per person annually. This encompasses waste produced at different stages like distribution, processing, manufacturing, primary production, and within households. Notably, household food waste makes up 52 % of this overall waste, as stated by (Schmidt et al. 2019). Additionally, (Klement et al. 2021) indicates that the nitrogen loss in the supply chain is 9.94 kg N per person annually. The nitrogen lost via household food waste is estimated to be 0.8 %, reflecting the average nitrogen content of local food.

The calculation details and references can be found in Appendix A :Reference for flow calculations

3.4. Assumptions and uncertainties

In order to fill the data gaps, a few assumptions were made.

- It's assumed that the weight gain of animals in the farm block mirrors the production of animal products.
- For human food consumption, it's postulated that half of the food is imported, while the other half is sourced locally.
- For forage consumption, the ratio of forage originating from local crop production to imported forage is assumed to be 3:2.

Furthermore, owing to the varied methodologies employed in data acquisition from different sources, there exists an inherent uncertainty in the data. This uncertainty is summarized in Table 3-2.

Table 3-2 Summary of uncertainty according to the form of data acquisition

Data acquisition	Uncertainty	Remark
Data directly from statistic of Barnim	5 %	Due to data protection measures, certain data are unavailable. However, this does not imply that their values are zero.
Data estimated by the share of Brandenburg	15 %	Data is only accessible at the federal state level. The values for Barnim are derived by scaling based on the proportion of relevant attributes or parameters from Brandenburg.
Data Barnim * literature value (with known uncertainty)	Literature value	Data is calculated based on the Barnim data and some literature data. The uncertainty associated with these literature values is documented.
Data Barnim * literature value (without known uncertainty)	30 %	Data is calculated based on the Barnim data and some literature data.
Data Barnim * literature value (lack of details)	50 %	e.g. lack of the weight of livestock for assuming the forage input.
Assumption	80 %	Assumed in this study without supporting documents.

4. Results

4.1. Result of Baseline Scenario 2016

4.1.1. Human metabolism

Regarding the material flow, the human block experienced a mass loss of 80,841 tons, which is 42.7 % of the total input of 189,414 tons in 2016. This loss can be attributed to human activities, such as sweat and fat being exhaled. In Barnim, the feces generated amounted to 9,755 tons, whereas urine generation was markedly higher at 98,819 tons. In total, urine represents 9 % of the human excreta and feces represent the remaining 91 %.The quantities of feces and urine processed in both the central wastewater treatment plants and the small wastewater treatment plants were scaled up according to the population connected to the central WWTPS, small-scale WWTPS, and collection pits. Notably, the central WWTPs handled approximately 98.9 % of feces and urine, with the remaining 1.1 % addressed by small-scale wastewater treatment plants.

Regarding the nitrogen flow, 255 tons nitrogen is lost from the system through human activities in 2016, forming 23.3 % of the overall nitrogen input, quantified at 1,093 tons. Conversely, 76.7 % nitrogen was present in human excreta. In 2016, urine accounted for 720 tons of the nitrogen generated, while nitrogen from feces alone accounted for a mere 118 tons. This indicates that the quantity of nitrogen in urine in Barnim was approximately six times that of feces in 2016. Furthermore, 829 tons of nitrogen within human excreta underwent treatment in central WWTPs, accounting for 98.9 %, and a scant 8.9 tons (1.1 %), was processed in small-scale WWTP, with a distribution similar to mass flow.

4.1.2. Wastewater Treatment Plant and Sewage Sludge

WWTP:

The contribution of municipal wastewater (excluding urine and feces) is pivotal in the wastewater treatment process, accounting for approximately 99.8 % and 99.7 % of the total input in central and small-scale WWTPs, respectively. The municipal wastewater used for centralized treatment also includes external water sources and rainwater, which account for about 1.9 % and 7.9 % of the municipal wastewater, respectively, and in 2016 were 851 thousand m^3 and 3,617 thousand m^3, respectively. In terms of output, the central WWTPs generated 20,764 tons of sludge, representing 0.04 % of the total production. Mass loss during treatment was 1,364,993 tons or about 3.0 % of the production, while the remaining 97 % was treated wastewater. Similar proportions are also reflected in small-scale WWTPs.

Regarding the nitrogen flow, the central wastewater treatment's total nitrogen input stands at 3,372 t, with municipal wastewater representing 75.4 %, feces 3.5 %, and urine 21.1 %. Of the outputs, 27.1 % of nitrogen is found in sewage sludge, 17.3 % remains in treated wastewater, and approximately 55.6 % is eliminated via gaseous emissions. In contrast, small-scale WWTPs see 3.8 % of nitrogen inputs from feces, 23.4 % from urine, and 72.8 % from municipal wastewater. Notably, 24.7 % of nitrogen exits the system in sewage sludge, with a nitrogen loss of 8.9 %, and 66.4 % persists in treated wastewater, attributable to the absence of a denitrification process.

Sewage sludge:

The sewage sludge block primarily receives its input from three sources: a dominant 98.8 % from central WWTP, a minimal 1 % from small-scale WWTP, and 0.4 % from imported sewage sludge. The treatment of this sewage sludge is predominantly managed through thermal methods, with 11,894 tons in year 2016, accounting for 56.6 % of the total sewage sludge output. In addition, a large amount of sewage sludge (5,725 tons) is transported to other states in 2016, and another 332 tons of sludge is transferred to different sewage treatment plants for treatment. All in all, 17,951 tons of sewage sludge, or 85.4 %, leaves the sewage treatment system. Conversely, 3,072 tons (or 14.6 %) of sewage sludge are reused as fertilizer and returned to the agricultural sector. This practice not only recycles part of the waste, but also utilizes it to enrich agricultural production.

Meanwhile, the total nitrogen input for the sewage sludge block is 926 t/a, of which 14.6 % of nitrogen is utilized for crop production, while 85.4 % exits the system.

4.1.3. Biowaste and OFMSW

In 2016, food waste in Barnim was estimated at 7,014 tons, of which only 24.4 % went into the dedicated biowaste collection system, while the majority (75.6 %) was misclassified as other waste types, indicating initial challenges after the introduction of biotin. Composting plants processed 24,767 tons of biowaste, mainly from green waste (90.0 %) and to a lesser extent from biobin (6.9 %) and other sources (3.1 %). 56.1 % of the composted output was converted into fertilizer, with the remaining 43.9 % mass loss.

In terms of nitrogen fluxes, household food waste resulted in 56 tons of nitrogen losses, 80 % of which was improperly sorted waste. The composting process obtained 11 tons of nitrogen from the biotin, which represents only a small part of the total input (6.8 %), the rest mainly coming from green waste (90.0 %). Outputs included fertilizers for crop production (43 tons), landscaping (30 tons) and private households (25 tons), with 67 tons lost in the process.

4.1.4. Crops

Crop Production:

Regarding the material flow, crop production inputs were substantial at 1,671,239 tons, sourced from fertilizers and humus reintroduction (27.9 %) and atmospheric contributions (72.1 %). The outputs were diverse: harvested crops (76.0 %), straw (18.4 %), grass for grazing (4.5 %), and a minimal loss (1.1 %), the latter due to omitted considerations of water runoff and evaporation.

In terms of nitrogen fluxes, the total nitrogen input was about 6,478 tons, of which 84.2 % came from fertilizers and the remaining 15.8 % from the atmosphere. Nitrogen is uptake from the atmosphere through rainwater deposition and nitrogen fixation. In 2016, nitrogen absorbed from the atmosphere included 149 tons from rainwater and 796 tons fixed by legumes and 77 tons from seeds, which accounted for 2.3 % and 12.3 % and 1.2 % of the total nitrogen input, respectively. In addition, municipal residues provided 0.8 % of the nitrogen (fertilizer from sewage sludge and OFMSW), while agricultural fertilizers provided 36.2 % of the nitrogen. Notably, the main N input was from mineral fertilizers, which accounted for 46.7 % of the N input. On the other side, the main output of nitrogen came from harvested crops, which accounted for 52.1 % of the total. Straw retained 7.4 % of the nitrogen, while grazing accounted for 1.7 %. Nitrogen loss was significant, with 38.7 % of nitrogen lost through gas emissions, runoff or leachate. However, the nitrogen stock still shows an abundance of 441 t nitrogen in the topsoil.

Crop Products and Straw:

Of the harvested crop blocks, 25.7 % is used as livestock feed, 5.0 % goes to the food industry for local consumption in Barnim and the remaining 69.3 % is exported to other regions. This distribution is consistent in terms of both material and nitrogen flows.

In 2016, a total of 82,771 tons of straw was collected, of which 9.4 % was used for animal bedding, 9.1 % was returned to the fields for humus balance, and 81.5 % was used for forage. In addition, the straw contained 456 tons of nitrogen, of which 8.5 % was used for bedding, 8.2 % was left in the field with the humus returned to the field, and notably, 83.3 % was available for livestock consumption.

Intercrops

In terms of material flow, the total input for intercrops was 59,363 t in 2016, with an contribution of 81.5 % and 18.5 % from the environment (air and water) and fertilizers, respectively. On the output side, 42,760 t of intercrops were harvested, of which a notable 84.4 % was used for producing livestock fodder and the remaining 15.6 % employed as green fertilizer to enrich soil nutrient content. In total, there was a 28 % mass loss from the system, equating to 16,603 tons in 2016. Additionally, the output from harvested intercrops constituted 12.6 % of the total harvested crop output.

Regarding nitrogen flow, intercrop production received 171 t of nitrogen, 28.8 % from fertilizers and the rest from environmental sources. Out of the total output, 22 t of nitrogen were lost, representing 12.7 %. Concurrently, 73.7 % of the nitrogen output was retained in intercrops used as green fertilizer, and 13.6 % was present in intercrops dedicated to forage production.

4.1.5. Farm (Livestock)

Fodder:

Regarding material flows, the total fodder input stood at 219,980 tons, composed of 26.5 % from imported forage, 39.8 % from crop production, 30.7 % from straw, and a minimal 3.0 % from intercrops. In the nitrogen flow, the majority (52.9 %) was from imported fodder, owing to the typical high energy and protein content in forage that isn’t usually self-produced. The remaining contributions were 31.7 % from crop production, 14.6 % from straw, and a nominal 0.9 % from intercrops.

Farm:

Regarding material flows, the farm’s input totals 740,253 t in year 2016, encompassing various sources such as grazing forage (20,225 t), fodder (219,980 t), straw for bedding (7,780 t), and a significant quantity of water input (492,268 t). The water consumption represents the largest share of the input, accounting for 66.5 % of its total, while the combined food intake for livestock (fodder and grazing) constitutes 32.4 %, and the straw used for husbandry purposes makes up 1.1 %.

In terms of output, the primary product is manure. This includes manure directly deposited on fields during grazing (2.9 %), collected manure that is immediately spread on fields (27.6 %), and processed manure along with digestate (25.7 %). In general, a substantial 97.4 % of the amassed livestock excreta (excluding manure from grazing) is utilized for crop cultivation, with the remaining 2.6 % allocated for intercrop production.

There is a notable loss within the livestock sector, amounting to 258,347 tons annually, (approximately 34.9 %). This loss is attributed to the inherent metabolic demands of livestock and the loss incurred during the storage and processing of manure.

In terms of nitrogen flow, the total nitrogen input was about 2,753 tons in 2016. Of this, a significant 94.7 % of nitrogen originated from fodder, with 3.9 % attributed to grazing activities and a minimal 1.4 % derived from straw used for bedding. There's a nitrogen loss of approximately 1.1 %, and 16.5 % of the nitrogen remains in farm products. The nitrogen output from livestock excrement is notably high, recorded at 2,269 tons, within which 50.3 % of nitrogen is present in digestate, 45.6 % in manure for direct application, and 4.2 % in manure from grazing.

Animal products:

In 2016, the production of animal products accounted for 65,996 tons, encompassing various categories: eggs (41 tons), meat (3,686 tons), and a substantial quantity of milk (62,269 tons). A significant portion, 46.6 %, of these farm products was exported to regions outside Barnim, while the remaining 53.4 % was consumed locally within Barnim. The distribution of nitrogen flow mimics the same proportions as the material flow.

4.1.6. Food process:

For food processing in 2016, the total input was 104,700 t. This input derived from several sources: regional crop products (16.4 %), regional farm products (33.6 %), and a hefty 50 % from imported food. Throughout the food processing stage, there's a loss of approximately 12.9 % of the food, attributed to factors like household food waste or losses occurring within the food supply chain. Conversely, 87.1 % of the food is processed and consumed by humans.

When it comes to the nitrogen flow, the total input stood at 2,932 t. The majority of this nitrogen (86.2 %) originated from imported food, with smaller contributions from regional crop products (5.5 %) and regional animal products (8.3 %). There's a considerable loss of nitrogen (60.8 %) during the food supply chain, and a further 1.9 % is lost due to household food waste. Ultimately, 37.3 % of the nitrogen is assimilated through human consumption.

In conclusion, the wastewater sector is the predominant contributor to the system (see Figure 4-1). The primary material flows are characterized by the input of municipal wastewater and the output of treated wastewater from central WWTPs, with losses occurring within central WWTPs. Regarding nitrogen flows (see Figure 4-2), the three predominant ones are harvested crops, mineral fertilizer, and fodder. Additionally, the system receives an import of 10,795 tons of nitrogen, with an export amounting to 10,354 tons. In terms of material flows, the import flows are quantified at over 4.8*10^7 tons, while the system exports around 4.7*10^7 tons.

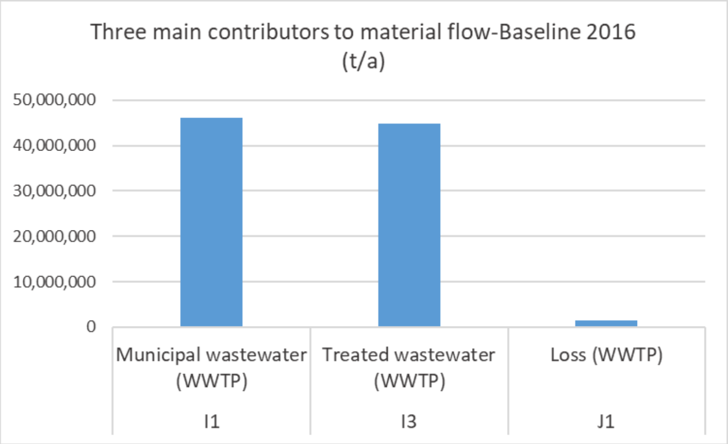


Figure 4-1 Three main contributors to material flow in baseline scenario 2016

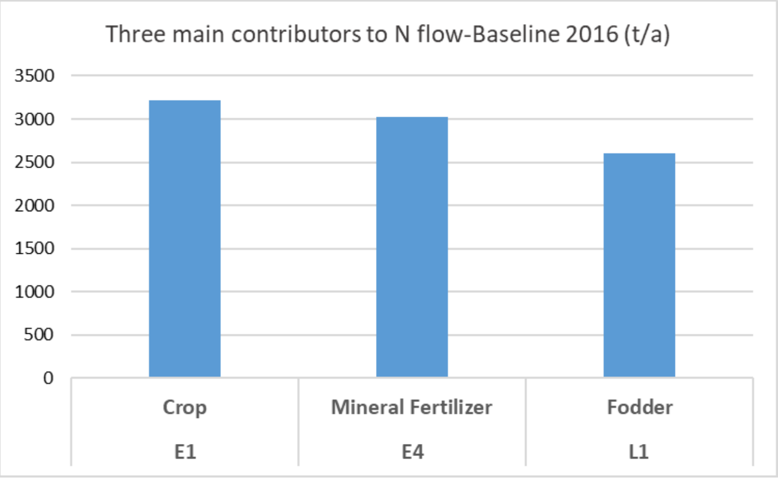


Figure 4-2 Three main contributors to N flow in baseline scenario 2016

4.2. Baseline 2020

4.2.1. Human metabolism

In terms of material flow, the "human metabolism block" encountered a loss of 84,429 tons mass for human activities, making up 42.7 % of the aggregate input that was recorded at 197,831 tons. In Barnim, the generation of feces reached 10,189 tons, amounting to 9 % of the total human excreta, while the generation of urine was substantially greater, standing at 103,213 tons (91 %). It's important to note that the central WWTPs managed roughly 99 % of the human waste, leaving a mere 1 % to small-scale WWTPs.

As for the nitrogen flow, the total loss during metabolism touched 274 tons in 2020, corresponding to 23.8 % of the total nitrogen input. In that year, urine accounted for 752 tons of nitrogen, while only 123 tons came from feces. In addition, 867 tons of nitrogen present in human waste was subjected to treatment in the central WWTP, comprising 99 %, and a mere 9 tons (1 %) was handled in small-scale WWTP.

4.2.2. Wastewater Treatment Plant and Sewage Sludge

WWTP:

Municipal wastewater flow (excluding urine and feces) is also crucial in the WWTP process in 2020, making up roughly 99.8 % and 99.7 % of the total input in both central and small-scale WWTPs. The municipal wastewater contained 910 and 3,937 thousand m^3 of external waster and rainwater, which equal to 2 % and 8.6 % of municipal wastewater, respectively. Regarding the outputs, the central WWTPs produced 23,390 tons of sludge, equivalent to 0.1 % of the total. A mass loss of 1,366,797 t, around 2.9 % of the total output, was noted, while the rest, 97.0 %, comprised treated wastewater. These ratios are similarly observed in small-scale WWTP.

Regarding the nitrogen flows, the total nitrogen introduced into the central WWTP amounted to 3,383 t, with municipal wastewater contributing 74.4 % %, feces 3.6 %, and urine 22.0 %. Concerning the outputs, 30.5 % of nitrogen is encapsulated in sewage sludge, 17.3 % stays in the purified wastewater, and roughly 52.3 % is dispelled through gaseous forms. Conversely, in small-scale WWTP, nitrogen contributions are 4.0 % from feces, 24.8 % from urine, and 71.4 % from municipal wastewater. Significantly, 30.6 % of nitrogen departs the system in sewage sludge, accompanied by a nitrogen loss of 3.0 %, and 66.4 % remains in the treated wastewater, due to the lack of a denitrification stage. A comparable distribution was also evident in the year 2016.

Sewage sludge:

Input to the sewage sludge block dominantly comes from the sewage sludge from central WWTPs, which equals to 98.7 % of the total input. The imported sewage sludge and sludge from small-scale WWTP only occupies 1.3 % in total, which is 0.4 % and 0.9 %, respectively.

The same phenomenon can be observed as in 2016 that most of the sewage sludge undergoes thermal treatment processes, with 12,825 tons in the year 2020, representing 54.1 % of the total sewage sludge output. Moreover, a substantial amount of sewage sludge (7,492 t) is transferred to the other states in 2020, with an additional 417 tons directed to alternative WWTPs for processing. Cumulatively, a significant quantity, 20,734 tons of sewage sludge (85.7 %), is extracted out of the system. On the other hand, 2,963 tons of sewage sludge find use as fertilizer (12.5 %).

Simultaneously, the total nitrogen input is 1,044 tons in 2020, with 12.5 % of the nitrogen being employed for agricultural cultivation, while the remaining 87.5 % is discharged from the system.

4.2.3. Biowaste and OFMSW

Regarding the material flows, 7,326 tons of food waste was wasted in household, going with 12,950 tons of other biowaste, was collected separately in biobin and treated in composting plant. Different from the small value of biowaste from biobin in 2016, there were 20,276 tons of biowaste collected in 2020, which is approximately 12 times bigger than that in 2016. In addition, the composting plants handled 47,951 tons of biowaste, chiefly composed of green waste (50.7 %), followed by biowaste from the biobin (42.3 %), and a nominal amount from additional streams (7.0 %). The main output of composting plant was fertilizer (36.9 %), alongside a considerable mass loss (63.1 %).

In terms of nitrogen flows, nitrogen loss from domestic food waste was recorded at 59 tons, and 74 tons of nitrogen from additional household biowaste. During composting, biowaste from biobin contributed 133 tons of nitrogen (41.9 %). And the green waste and the other biomaterial for composting contributed 51.0 % and 7.1 %, respectively. The composting output was diversified among crop production fertilizer (60 tons), landscaping applications (34 tons), and private household use (30 tons), with a pronounced loss of 193 tons during the processing phase.

4.2.4. Crops

Crop Production:

In terms of material flows, inputs for crop cultivation reached 1,534,162 tons in 2020, derived from fertilizers and hums (26.7 %) and environmental deposition (73.3 %). Outputs were varied: crops harvested (75.7 %), straw (18.7 %), pasture grass for grazing (4.8 %), and a minor loss (0.8 %).

For nitrogen fluxes, nitrogen inputs accounted to around 5,048 tons, with a dominant 76.8 % sourced from fertilizers and humus and 23.2 % from other nitrogen input. In 2020, atmospheric nitrogen captured included 163 tons from rainfall and 930 tons via legume fixation, adding respectively 3.2 % and 18.4 % to the total nitrogen input. Additionally, 79 tons of nitrogen is imported as seeds and assisting materials (1.6 %). Furthermore, fertilizer from municipal residue contributed 1.4 % of the nitrogen, while agricultural fertilizers accounted for 74.7 %. The total nitrogen output was linked to crop harvesting, claiming 57.5 % of the total. Straw contributed 8.1 % of the nitrogen, with pasture for grazing accounting for an additional 2.1 %. Losses were substantial, with 32.1 % of nitrogen escaping as gas, runoff, or leachate, leading to 80.8 tons surplus in soil nitrogen reserves.

Crop Products and Straw:

Within the harvested crop, 24.7 % serves as animal feed, 5.6 % is channeled into local food production in Barnim, and the 69.7 % is exported to the other region. This allocation is similar in both material and nitrogen flows.

In 2020, 78,359 tons of straw was gathered, of which 9.7 % was purposed for livestock bedding, 9.0 % reintroduced to soil as humus, and a significant 81.3 % was used as fodder. Regarding the nitrogen flow, 9.2 % N was contained in bedding straw, 8.6 % was reincorporated into the soil with humus, and a substantial 82.3 % was allocated for animal nutrition.

Intercrops

In terms of material flows, intercrops received a combined mass input of 79,680 tons in 2020, with fertilizers and environmental resources (air and water), providing 19.7 % and 80.3 % respectively. Regarding the output, 49,819 tons of intercrops were reaped, of which a 41.9 % was designated for livestock feed production, while the rest (58.1 %) was applied as green fertilizer, enhancing soil fertility. The system witnessed a 37.5 % mass loss.

Regarding nitrogen fluxes, the input for intercrop cultivation was with 210 tons of nitrogen, with 33.6 % attributed to fertilizers and 66.4 % from environment. From the total output, 36 tons of nitrogen was lost, equivalent to 17.1 %. Simultaneously, a 48.2 % of the nitrogen yield was conserved in intercrops employed as green fertilizer, and 34.7 % was inherent in forage-production.

4.2.5. Farm (Livestock)

Fodder:

In 2020, the total forage inputs were 214,958 tons, with imported fodder contributing 24.3 %, forage from crop production at 36.4 %, straw at 29.6 %, and 9.7 % from intercrops. Regarding the nitrogen flow, a significant portion, 57.9 %, came from imported forage, Other nitrogen sources included 27.0 % from crop production, 12.4 % from straw, and a mere 2.7 % from intercrops.

Farm:

Regarding the material flows, total farm inputs for the year 2020 were 657,422 tons, encompassing diverse origins like grass from grazing (20,192 tons), forage (214,958 tons), straw for bedding (7,593 tons), and a large amount of water (414,678 tons). Water constituted the majority, with 63.1 % of overall inputs, while the total feed for animals (forage and grazing) was 35.8 %, and straw for animal care accounted for 3.1 %.

In the output, manure stood out as the primary product. This category includes manure directly left on fields through grazing (3.0 %), gathered manure directly applied to fields (20.8 %), and digestate (30.4 %). In addition, a significant loss is observed in the livestock section, accounting to 220,101 tons per year (33.5 %).

Regarding nitrogen flow, the total nitrogen inputs were around 2,881 tons in 2020. Here, a considerable 95.0 % of nitrogen came from fodder, 3.7 % resulted from grazing, and 1.3 % was from straw used as bedding. In addition, there was a nitrogen loss of approximately 12.2 %. 16.7 % of the nitrogen persisting in farm products, 41.6 % of nitrogen in digestate, 26.1 % in manure, and 3.3 % in grazing manure.

Animal Products:

In 2020, animal product production reached 64,987 tons, with three main product groups: eggs (77 tons), meat (4,794 tons), and a notable volume of milk (60,115 tons). A considerable 43.4 % of these agricultural products was distributed to areas beyond Barnim, while the rest, 56.6 %, catered to local consumption within Barnim. The nitrogen flow distribution followed a similar pattern to the material flow.

4.2.6. Food Process

For the food processing sector in 2020, the total material inputs were 109,348 t, sourced from regional crop products (16.4 %), regional farm products (33.6 %), and a substantial 50 % from imported goods. During the food processing phases, there was a loss alone the supply chain, of roughly 12.9 %, which means that the remaining 87.1 % of the food underwent processing and ended up as human food.

The majority of this (86.3 %) comes from imported food products, with a small amount (5.5 %) coming from regional crop products and regional livestock products (8.2 %). Nitrogen losses in the supply chain were considerable at about 60.7 %, with an additional 1.9 % coming from household food waste. Finally, 37.3 % of nitrogen is ingested through the human diet.

Figure 4-3 and Figure 4-4 show the three main contributors to material flows and to the nitrogen flows. In summary, the wastewater sector is the main contributor to the system. The largest material flows are the input of municipal wastewater and output of treated wastewater and the losses occurring within the central WWTPs. In terms of nitrogen flows, the most significant are harvested crops, fodder and imported food. In addition, the system imports 10,039 tons of nitrogen and exports 9,958 tons. In terms of material flows, imports exceeded $4.8*10^7$ tons, while the system exported about $4.7*10^7$ tons.

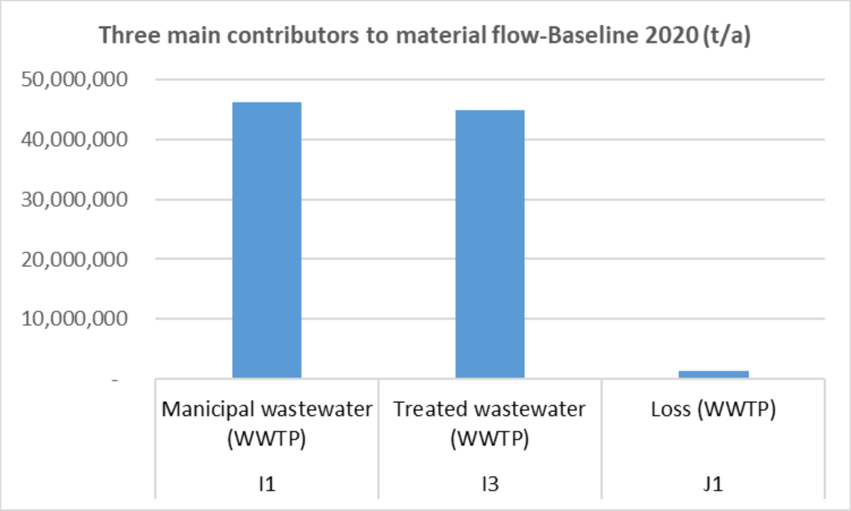


Figure 4-3 Three main contributors to material flow of baseline scenario 2020

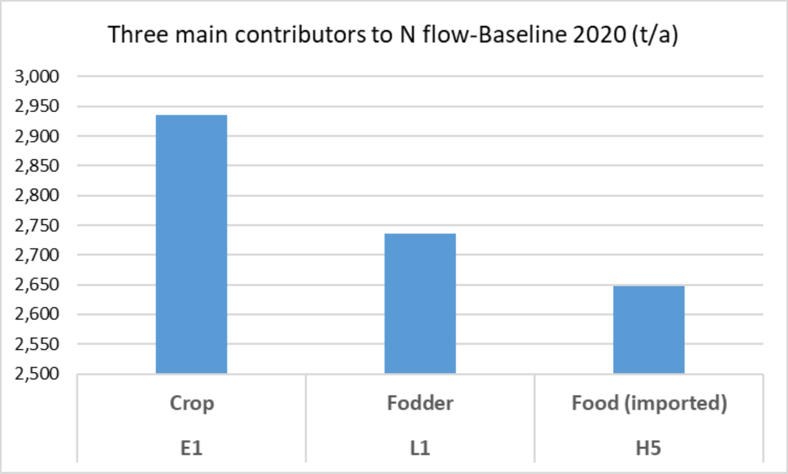


Figure 4-4 Three main contributors to nitrogen flow of baseline scenario 2020

4.3. Result of thermophilic composting plant

The baseline for the human waste composting plant was established based on the annual data from the Finizio pilot thermophilic composting plant in 2022. The results of the modeling are available in Table (appendix) C-1. The primary input for the dry toilet system consists of 90.2 % urine, 7.6 % feces, and 1.9 % toilet paper, supplemented by 0.2 % straw and 0.1 % shredded green waste to minimize odor. The plant's annual urine treatment capacity is 133 t/a. In 2022, the plant received a total of 800 tons of urine, of which 667 tons were discarded through the sewage system. The urine is then stabilized and purified using active carbon before evaporation. The same amount of nitrogen remains in the liquid fertilizer, showing an 80.5 % reduction during this process.

The other input from the dry toilet includes feces, and impurities, which are then hygienized, resulting in an estimated 10 % mass loss. Following an intensive hygienization period, the solid material is combined with water, biomaterials (such as meadows, leaves, and grass cuts), plant carbon, additional shredded green waste, and clay material to adjust the C/N ratio and moisture content. After four composting trials, 110 t of unsieved humus fertilizer was produced. This humus was subsequently sieved, resulting in 59 t of final humus fertilizer and 59 t of oversized grain humus fertilizer, with 28.0 % of the final humus fertilizer and 36.1 % of the oversized grain humus fertilizer being reintroduced to the humification process. 38 t oversized grain humus stayed in the stock. Overall, the pilot plant generated 42 t of humus fertilizer, with 0.19 t found as sieve residue, wherein non-degradable tissue was the most common foreign material identified during sampling. A total of 79 t of mass was lost during the humification process. Figure 4-5 shows the material mass fraction of all the input material during the humification process.

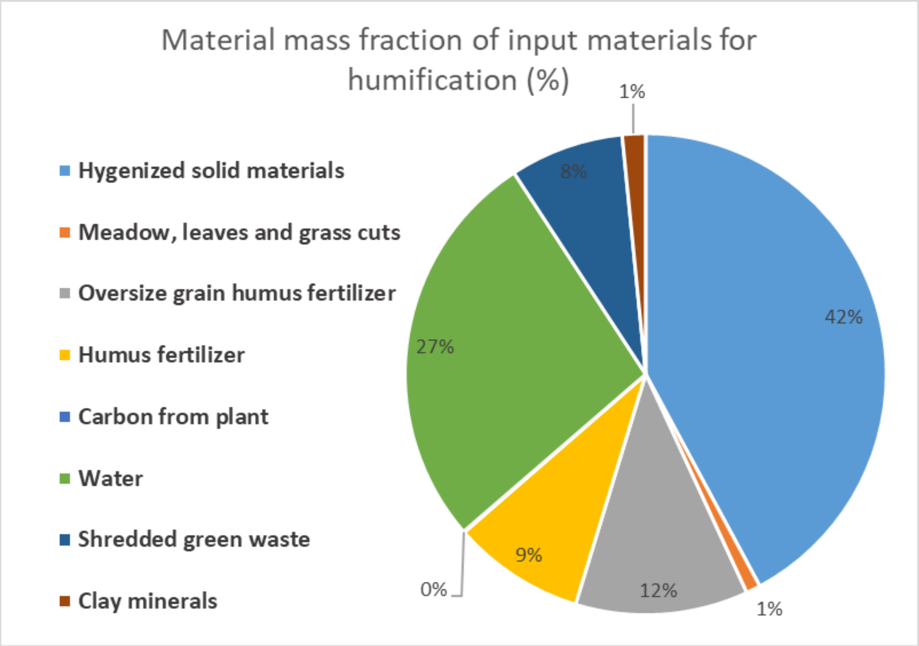


Figure 4-5 Material mass fraction of input material of humification

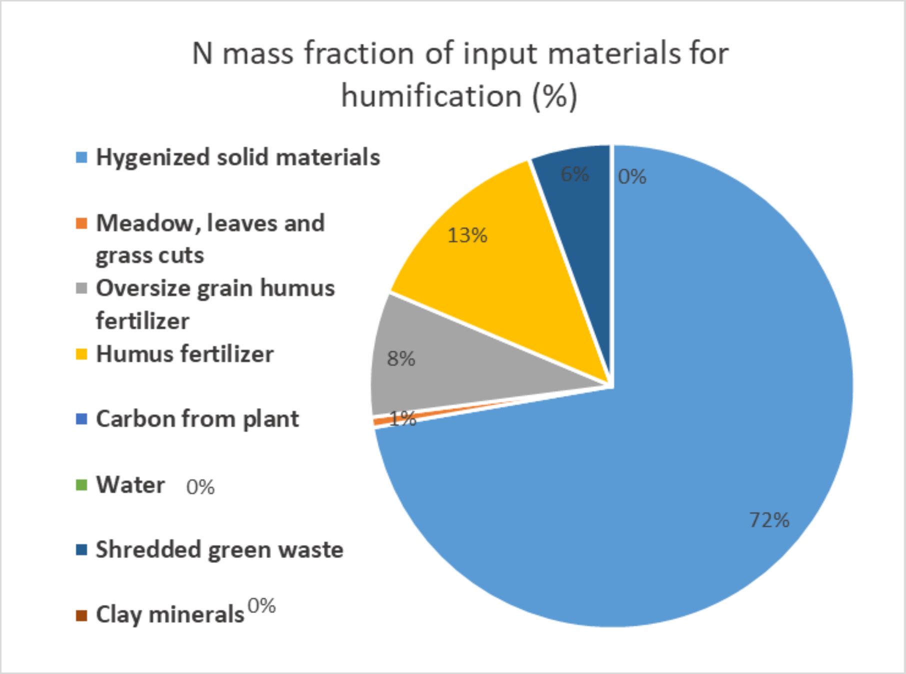


Figure 4-6 Nitrogen mass fraction of input material of humification

Regarding nitrogen flow, the most significant nitrogen mass flow in 2022 was observed in urine, accounting for 6.1 t. However, only 1 t of nitrogen from the urine was retained in the liquid fertilizer due to the plant's limited urine treatment capacity. The feces solids combined with impurities contained 0.74 t of nitrogen, and 36.5 % (0.27 t) of nitrogen was lost during the hygienization process, while an additional 0.12 t of nitrogen was lost during humification. Ultimately, 0.22 t of nitrogen was yielded in the humus fertilizer in 2022. Figure 4-6 shows the nitrogen mass fraction of all the input material during the humification process.

4.4. Flow results of scenario study

The scenario study (theoretical, technical and future scenarios) is derived from the baseline scenario 2020. The input material of the dry toilet and human waste composting process are calculated based on the proportion of baseline thermophilic composting plant in year 2022.

4.4.1. Material flow

Theoretical scenario

In this theoretical scenario, all urine and feces generated in the Barnim region are presumed to be separately collected via dry toilets for nutrient recycling. This results in 103,213 t of urine and 10,189 t of feces being diverted from the wastewater treatment system to the dry toilet process. These are combined with 2,547 t of dry toilet paper, 182 t of shredded green waste, and 243 t of straw. In the urine treatment stage, 543 t of active carbon is used to eliminate impurities from the liquid urine. For feces treatment, 13,162 t of feces solids mixed with impurities undergo a hygienization process, during which 1,316 t is lost through mass reduction, leaving 11,845 t of hygienized solid material as output. This output is then blended with 10,507 t of other input materials (including 0.2 % carbon from plants, 20.5 % shredded green waste, 4.2 % clay minerals, 2.6 % meadow, leaves, and grass clippings, and 72.6 % water). Additionally, 3,183 t of oversize grain humus fertilizer and 2,433 t of final humus fertilizer are incorporated in the humification process. In total, 11,849 t of mass is lost through humification. After sieving, 6,387 t of humus fertilizer is produced, approximately 152 times more than the humus fertilizer generated in the baseline pilot plant in 2022. This implies that recycling all the feces in Barnim would require 152 composting plants with the same capacity as the Finizio composting plant.

In the composting plant, 5,834 t of green waste, sourced from the input for treating the separately collected organic fraction of OFMSW, is shredded to ensure sufficient shredded green waste for both the dry toilet process and humification. Of this, 3,500 t of woody oversize, a by-product of the shredding process, is returned to the treatment of separately collected OFMSW. Consequently, from the Barnim regional perspective, 2,334 t less green waste is processed in the central organic waste treatment, and only 8,145 t of fertilizer is generated for agriculture.

In comparison to baseline 2020, the adoption of dry toilets leads to conservation of water for toilet flushing, resulting in a reduction of municipal wastewater (excluding urine and feces) from 46,227,258 t to 43,555,821 t sent to the central WWTP with a reduction of 5.8 %, and from 407,416 t to 381,113 t in small-scale WWTPs with a reduction of 6.5 %. Additionally, 83,086 t of wastewater from urine evaporation process in urine treatment is disposed of in the central WWTP, culminating in a total wastewater input reduction of 2,775,425 t. Furthermore, this decreased wastewater input results in a reduction of sewage sludge generation from 23,697 t to 17,680 t, with 2,210 t of this sewage sludge (12.5 %) being utilized in agriculture.

Despite the reduced input of fertilizer derived from sewage sludge and the treatment of separately collected organic fractions of OFMSW, the total fertilizer input sees an increase due to the new recycled fertilizers from the composting plant. Liquid fertilizer (from urine) and humus fertilizer (from feces) contribute to an additional 26,514 t of fertilizer input.

Technical scenario

In the technical scenario, different from theoretical scenario, the urine and feces from the residents with the connection to the central WWTP will still be led to central WWTP. Thus, only 10,154 t urine combined with 1,002 t feces can be collected in the dry toilet and be treated in the thermophilic composting plant. This leads to an input of 251 t of toilet paper and additional 24 t of straw. In the urine treatment part, 10,154 t urine is treated, purified and condensed to 1,980 t liquid fertilizer with 8,174 t wastewater to be led back to central WWTP plant. According to the urine treatment capacity of this treatment plant (133 t/a), the whole urine treatment demand in Barnim would still requires 76 urine treatment plant. Additionally, in the process of feces management, 1,295 t of fecal solids are subjected to hygienization. This phase experiences a material loss of 130 t, culminating in 1,166 t of sanitized solid substances. And after humification, 1,588 t unsieved humus fertilizer will be sieved, in which 321 t oversize grain humus fertilizer and 246 t humus fertilizer are fed back to the humification process, and 633 t humus fertilizer can be produced in the end. The mass loss during the humification process is 1,179 t.

Within the composting facility, 574 t of green waste, originating from the treatment of OFMSW, undergoes shredding. Notably, 344 t of the resulting woody oversize, an outcome of the shredding operation, is redirected back into the processing of the separately collected OFMSW. Viewed from the Barnim region's standpoint, this translates to a decrease of 230 t in green waste managed at the centralized organic waste treatment facility, concurrently yielding 8,522 t of agricultural-grade fertilizer.

In the technical scenario, the wastewater decreases due to the saving of toilet flushing water is 239,110 tons which all come from the region with the connection to collection pits in comparison to the baseline scenario 2020. In small-scale WWTPs, 26,302 t municipal wastewater (exclude urine and feces) input is saved. This leads to a reduction rate of 0.5 % and 6.5 % respectively. Furthermore, 8,174 t urine evaporation water is led to the WWTPs. But in total, the wastewater input is still shows a decrease. In the sewage sludge generation, 21,762 t sewage sludge will be generated, from which 2,720 t will be used in the agriculture and crop production. This represents a 8 % reduction in comparison to the baseline 2020.

In total, the technical scenario will produce less liquid fertilizer from urine and final humus fertilizer from feces in comparison to the theoretical scenario, with a total human waste recycled fertilizer input of 2,613 t. This means that only around one tenth of the theoretical recycle fertilizer production can be technically achieved.

Future sustainable scenario

In the future sustainable scenario, the population is assumed to raise by 5 % based on the baseline scenario 2020 of Barnim region. This results in an increase in the total feces and urine generation to 10,698 t and 108,374 t respectively. 1,053 t feces and 10,662 from these can be feasibly collected in dry toilet and recycled. Same as theoretical and technical scenarios, the implementation of dry toilet will also lead to a drop of wastewater. Additionally, the sustainable scenario also suggests the usage of household grey water filter systems for a smarter waster reuse in rural household. Thus, the wastewater from the regions with connection to collection pit can also be reduced. All in all, in comparison to the baseline 2020, the municipal wastewater (feces and urine excluded) for central WWTPs drops to 44,407,302 t with a reduction of 4 %, even with a growth in the population. The municipal wastewater (feces and urine excluded) for small-scale WWTP also decreased to 400,169 t in comparison to the baseline scenario 2020.

In the sewage sludge generation section, 21,596 t sludge is produced. According to the new legislation regarding the sewage sludge usage, it is assumed in this study that, the sewage sludge from small-scale wastewater treatment plant will still be used as fertilizer in agriculture section. While among the central WWTPs in Barnim, the wastewater treatment plant in Schönerlinde, Eberswalde, Werneuchen, Joachimsthal have a capacity over 10,000 residents, with a sum of 812,000 residents. While Lunow, Lobetal, Marienwerder, Lanke Bogensee, Sydower Fließ, Krummensee, Breydin and Blütenberg schorheide have a capacity lower than 10,000 residents, with a sum of 14,870 residents. Thus, the share of those two categories are 98 % and 2 %. It is then assumed that 98 % of the sewage sludge in year 2030 should consider the phosphor recycling, while 2 % of the sewage sludge can still be used as the fertilizer in agriculture. In total, 20,981 t sewage sludge will go through the phosphor recycling process, and 189 t sewage sludge can be reused on the field.

In terms of human behaviors, it is assumed that more people will pay attention to a sustainable life style, in which people will consume more local food instead of imported food. In the future model, 27,128 t food will still be imported, while 81,405 t food is produced in the Barnim region. Moreover, more people will choose to consume crop-based protein and eat less animal-based protein, which leads to an increase in the crop product for regional consumption to 38,809 t and a decrease in animal-based product to 42,596 t.

It is also assumed that less food will be lost during the production and supply chain as well as in household. The food waste from supply chain drops to 4,047 t while the food waste from household is 4,654 t. Biowaste from biobin combining with green waste and the other bio material is then be composted, which produces 17,022 t fertilizer. 8,249 t is then used as fertilizer got agriculture, which contributes 48.5 % of the total fertilizer generated from OFMSW section.

Another big change in the future sustainable scenario is the livestock husbandry. The cattle number drops 10 %, which is assumed that the cattle manure will also drop 10 %. In general, the manure for direct use on field decreases 8.9 % with a mass of 124,750 t. Additionally, in comparison to the baseline 2020, the animal products (beef and milk), forage for cattle as well as the water consumption for cattle will also decrease, which leads to a reduction in the total animal production of 9.3 % (58,939 t), 8.4 % of total forage demand (196,806 t) and 8.2 % of water for livestock (381,133 t).

In the human waste recycling part, 10,662 t urine and 1,053 t feces with 263 t toilet paper and 25 t straw collected from dry toilet, can produce 2,079 t liquid fertilizer and 655 t humus fertilizer. In the composting plant 136 t and 1,252 t mass are lost through hygienization and humification process, respectively.

4.4.2. Nitrogen flow results

In the theoretical scenario, 752 t of nitrogen in urine and 123 t of nitrogen in feces are introduced into the composting plant. Within this process, 100 % of the nitrogen in urine remains in the liquid fertilizer. Of the nitrogen in feces, 128 t stays in the solid form mixed with impurities, and following hygienization, 13 t of nitrogen (10.0 %) is lost through mass loss, leaving 115 t of nitrogen in the hygienized solid. During the humification process, an additional 15 t of nitrogen is contributed through supplementary materials, combined with 17 t of nitrogen from the return flow of oversize grain humus fertilizer and 13 t from the return flow of humus fertilizer. Moreover, 78 t of nitrogen is lost during humification. In total, the final humus fertilizer contains 33 t of nitrogen, which can be recycled in agriculture. As indicated in the material flow, the total nitrogen input in the treatment of separately collected OFMSW also diminishes. This process receives 123 t of nitrogen from green waste and 23 t of nitrogen from woody oversize, with the resulting agriculture fertilizer from this segment dropping to 57 t of nitrogen.

Additionally, despite the reduction in the volume of municipal wastewater (excluding urine and feces), the nitrogen content remains consistent. The nitrogen present in the produced sewage sludge is 787 t, of which 97.5 t is reintroduced to agriculture. Overall, the total nitrogen loss from crop production escalates from 1,632 to 2,008 t, primarily due to the application of liquid fertilizer (from urine), accounting for approximately 376 t. The humus fertilizer contributes to a 3 t nitrogen loss. Consequently, the nitrogen stock is 454 t.

The total nitrogen input into the crop production as well as different fertilizer share from the total fertilizer input can be seen in the following figure Figure 4-7. 79 % of the total nitrogen input is accomplished by various fertilizers while only 20 % of the nitrogen comes from the environment. Among all the nitrogen input, mineral fertilizer occupies 29 % of the total fertilizer input, following with digestate (20 %), liquid fertilizer from separately urine treatment (13 %) and manure for direct use (11 %). The rest fertilizer all show a miner share on the total input within the range of 0-2 % of the total fertilizer share.

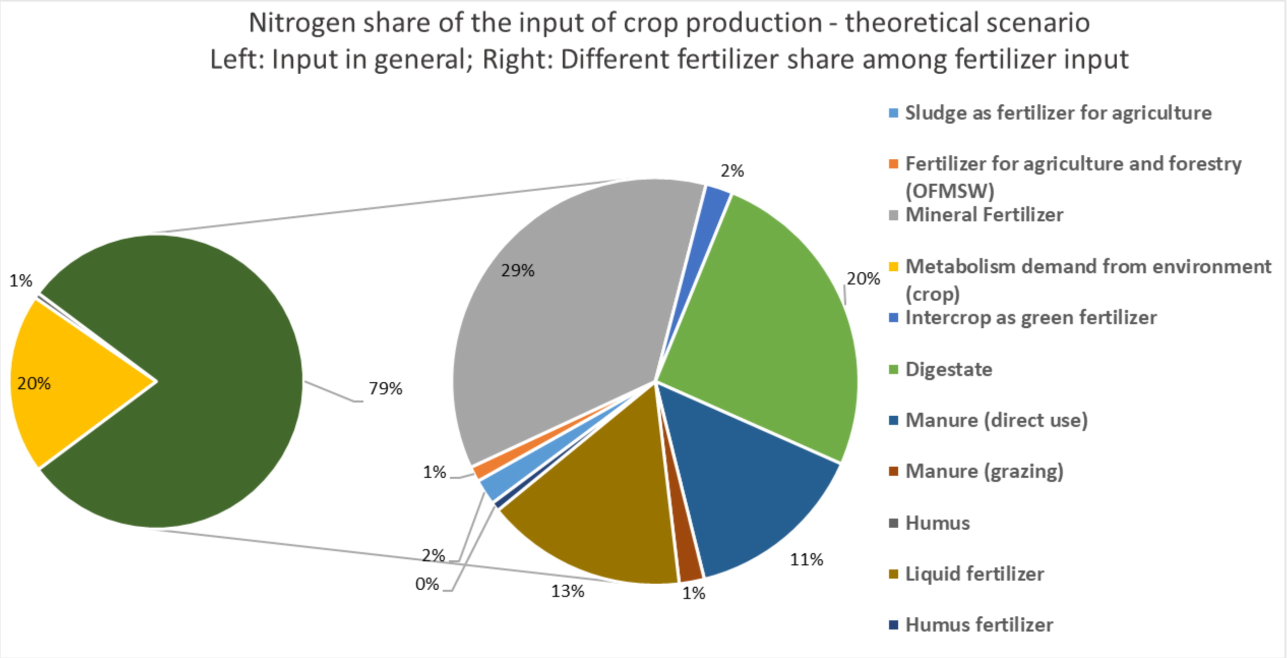


Figure 4-7 Nitrogen share of the input of crop production-theoretical scenario (Left: input in general; Right: Different fertilizer share among fertilizer input)

In the technical scenario,74 t of nitrogen present in urine and 12 t in feces are channeled into the composting facility. Throughout this procedure, the same result can be seen that the entirety of nitrogen found in urine is retained within the liquid fertilizer. Regarding the nitrogen in feces, 12.6 t persists within the solids amalgamated with impurities. Furthermore, there's a mass loss of 1.3 t of nitrogen (representing 10 %) during the hygienization, resulting in 11.3 tons of nitrogen in the sanitized solid. Throughout the humification stage, an extra 1.5 t of nitrogen is introduced via ancillary substances, amalgamated with 1.7 t of nitrogen from the recirculating oversize grain humus fertilizer and 1.3 t from the humus fertilizer's recirculation. Furthermore, there's a loss of 7.8 t of nitrogen during the humification. Cumulatively, the concluding humus fertilizer encompasses 3.3 t of nitrogen, available for agricultural recycling. As delineated in the material flow, there's also a tapering in the nitrogen input in the treatment of the separately harvested OFMSW. This phase acknowledges 157 t of nitrogen from green waste and 2.3 t from woody oversize, with the consequent fertilizer for agriculture from this division receding to 60 t of nitrogen.

Moreover, the nitrogen in the generated sewage stands at 900 t, from which 109 t is repurposed for agricultural use. In a comprehensive view, the total nitrogen lost from crop cultivation surges from 1,633 to 1,668 t. In the end, the nitrogen inventory stands at 113 t.

The total nitrogen input into the crop production as well as different fertilizer share from the total fertilizer input can be seen in the following figure Figure 4-8. In the technical scenario, the same tendency can be seen in the general nitrogen input in the crop production, with a slightly lower share for the total fertilizer input. Among all the fertilizer applied, mineral fertilizer still shows a significant share (32 %) followed by digestate (23 %) and manure for direct use (13 %). In the technical scenario, liquid fertilizer has a notably smaller share than in theoretical scenario (1 %).

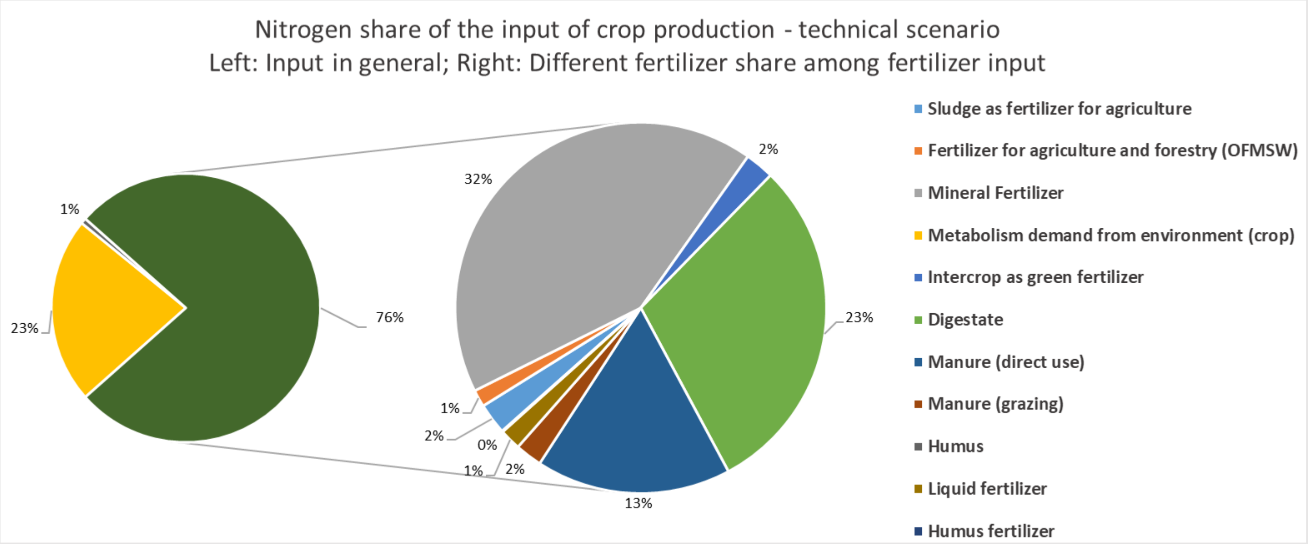


Figure 4-8 Nitrogen share of the input of crop production-technical scenario (Left: input in general; Right: Different fertilizer share among fertilizer input)

In the future sustainable scenario, the total nitrogen from feces and urine increased to 123 t and 752 t, in which 77.7 t nitrogen from urine goes through the urine treatment and stays in the liquid fertilizer. 12.7 t nitrogen from feces combined with 0.24 t nitrogen from toilet paper and 0.13 t nitrogen from straw is the hygienized with 1.32 t nitrogen loss. 11.9 g hygienized solid waste mixed with 1.55 t nitrogen from other assisting materials is then composted and sieved. 1.73 t nitrogen from oversize grain humus fertilizer and 1.32 t humus fertilizer are then fed back to the compost windrow. In the end, 3.4 t nitrogen from final humus fertilizer is yielded.

In the central WWTP, with the reduction of wastewater, nitrogen content of the municipal wastewater also reduces to 2,379 t. The output of the WWTP is 1,668 t nitrogen loss, 545 t nitrogen in treated wastewater and 994 t nitrogen in sewage sludge. In total, 27 t nitrogen in the sewage sludge will be used as fertilizer for agriculture, while 979 t nitrogen from sewage sludge will be exported from the system.

In the food process, a significant amount of nitrogen reduces in both food waste from household and in food waste from supply chain. The nitrogen found in household food waste stays 29 t while the nitrogen lost in food supply chain reaches 1,075 t. In OFMSW treatment block, regarding the less food waste from household, the generation of the nitrogen in biowaste from biobin also decreased to 115 t. In addition, 58 t nitrogen in the compost from OFMSW will be brought back to agricultural production.

In the future scenario, 10 % less cattle results in a less forage demand and less manure output, with new flows of 2,553 t nitrogen and 627 t nitrogen respectively. Less manure input highly impacted the nitrogen surplus in the soil in the crop production, with 7.2 t nitrogen surplus in 2030 scenario. In addition, 1,626 t nitrogen is lost through the agricultural section due to the application of fertilizers. The total nitrogen in put into the crop production as well as different fertilizer share from the total fertilizer input can be seen in the following figure Figure 4-9.

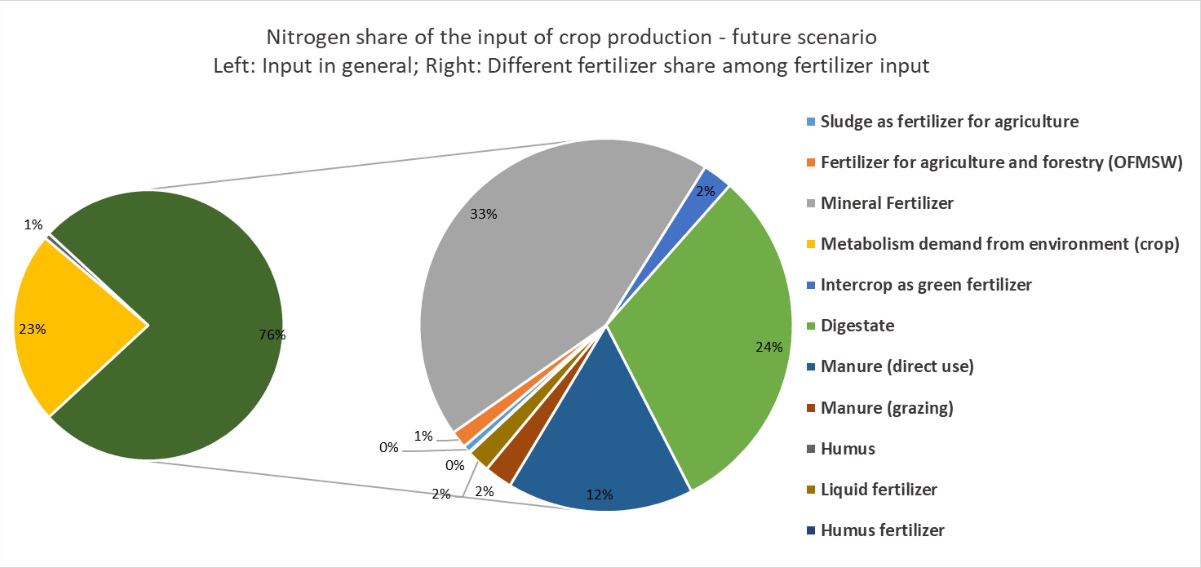


Figure 4-9 Nitrogen share of the input of crop production-future sustainable scenario (Left: input in general; Right: Different fertilizer share among fertilizer input)

In general, the future scenario still keeps a positive nitrogen surplus. But due to the reduction of the total fertilizer input, the nitrogen stock surplus drops significantly. The nitrogen input from the human waste (liquid fertilizer and humus fertilizer) has a miner impact in the whole fertilizer input. This means that in the future, with a reduction in animal husbandry and manure generation, the nitrogen surplus in the soil will still stay positive.

5. Discussion

5.1. Comparison of scenarios

5.1.1. Baseline scenario comparison

In the human block, the population escalated from 179,365 in 2016 to 187,343 by 2020, reflecting an approximate 4.45 % growth over this four-year span. While the distribution ratios of the amount of urine and feces treated in centralized and small-scale WWTPs remain unchanged, the sheer population increase has augmented the total urine and feces output and consequently, the nitrogen content for 2020.

Within the Centralized WWTPs, sewage sludge production in 2020 is significantly higher than in 2016 by 12.6 %. The input-output dynamics of the WWTP remain similar in the two base years. Intriguingly, despite the surge in sewage sludge production in the sewage sludge sector, the proportion of sewage sludge being reused as agricultural fertilizer is decreasing, from 14.6 % of total sewage sludge in 2016 to only 12.5 % in 2020.

One notable difference between the 2016 and 2020 scenarios relates to the section of the municipal biowaste treatment. It is worth noting that 2016 was the first year of implementation of the biowaste bins, and therefore a much smaller amount of biowaste was generated compared to 2020. Large amounts of food waste are invariably misallocated to the mixed municipal waste categories. In contrast, the amount of biowaste in the biobin in 2020 is greater than household food waste, which may be because some of Barnim's garden waste is mixed with food waste, all of which is collected in the biobin. By 2020, the amount of total nitrogen in biowaste reaches 133 tons, in contrast to 11 tons in 2016. The total generation of fertilizer produced from OFMSW composting plants increased slightly during this period, as well as the application as agricultural fertilizers. It is worth noting that the losses in both the material and nitrogen streams during treatment of OFMSW are much higher in 2020 compared to 2016.

In the livestock sector, the number of cattle, pigs, sheep and goats increased in 2016 compared to 2020, leading to an increase in manure production in that year. However, animal forage intake increased in 2020. This is because in 2020, there was 18,605 chickens and 147,100 poultry from various species (including geese, ducks and turkeys) raised in Barnim. This contrasts with 10,481 chickens and 10,929 other poultry in 2016. The total poultry husbandry in 2020 was approximately eight times higher than in 2016. Concomitantly, the estimated amount of forage for poultry in 2020 is approximately night times that of 2016, thus impacting the material and nitrogen flows.

In the crop production sector, crop and straw production in 2020 is reduced compared to 2016. Remarkably, in both reference years, the main output streams of the crop production system are attributed to crop products. However, there is also a notable difference in the change in nitrogen (N) stocks. In 2016, the surplus of N was 441 tons, which plummets to only 81 tons N in 2020, mainly due to a reduction in the use of mineral fertilizers. According to (Offergeld 2023), there was a significant surge in nitrogen fertilizer purchases between 2014 and 2016. However, by 2020, nitrogen mineral fertilizer purchases decline to 60,711 tons of nitrogen, the lowest level since 2008. This decline significantly reduces the total N input of mineral fertilizers to the crop production sector. It is important to note, however, that the model's mineral fertilizer consumption premise, which is based on procurement data, may not accurately reflect actual application levels, introducing a potential bias.

In terms of intercrops, 41.9 % of intercrops were used for animal fodder and 58.1 % for green fertilizer in 2020. This contrasts with the situation in 2016, where only 15.6 % of intercrops were allocated to forage production and 84.4 % were used as green fertilizer. Interestingly, even though the total production of intercrops increased in 2020, the use of intercrops as green fertilizer decreased by 19.8 %.

Figure 5-1 presents the main changes in material flows in 2020 compared to 2016. "Plus" indicates an increase in the flow mass, whereas "minus" signifies a decrease in the flow mass.

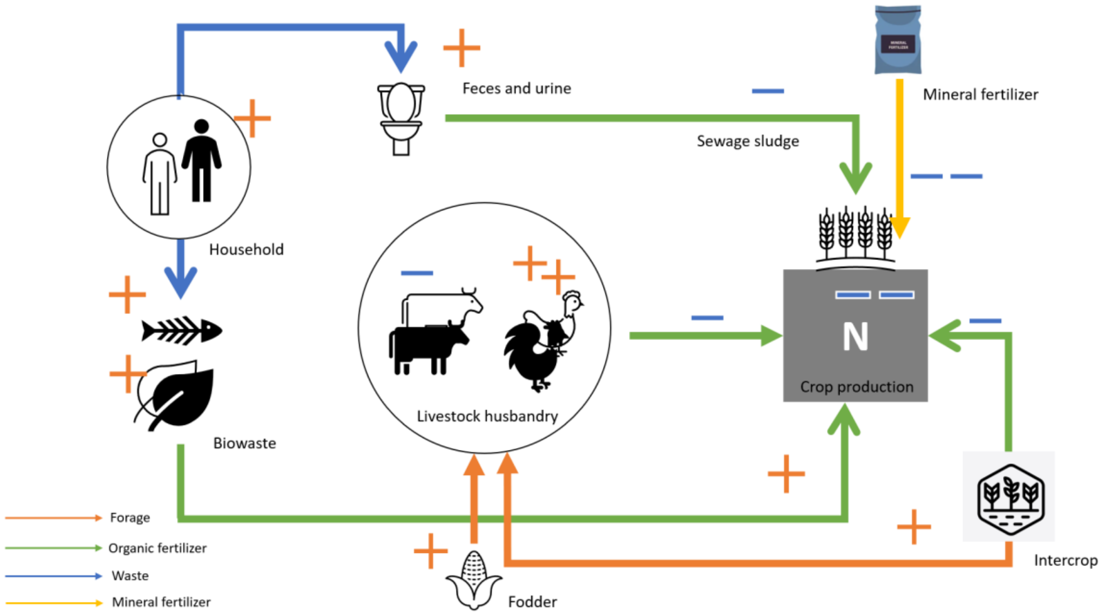


Figure 5-1 Simple view of the main changing material flows in 2020 relative to 2016 (N flow shares the same trend)

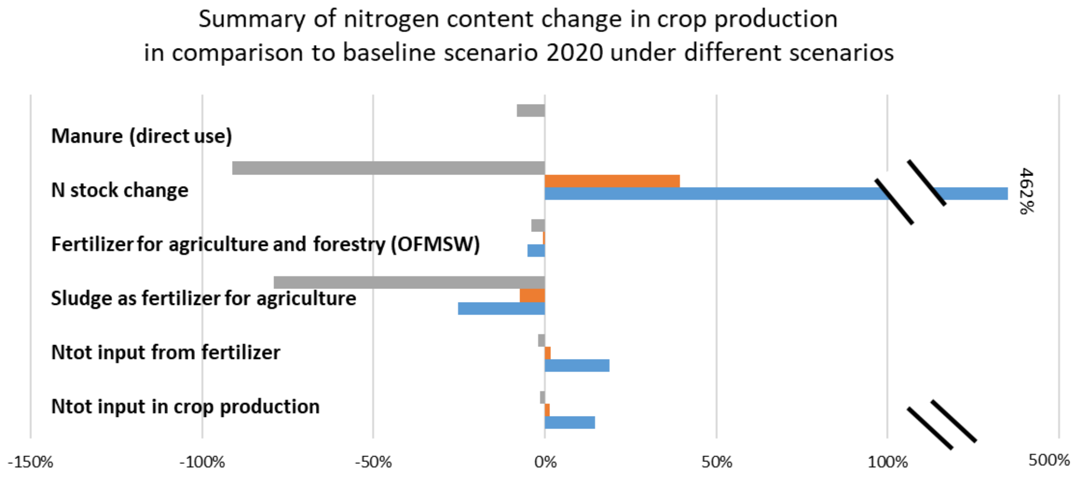
5.1.2. Comparison of scenario studies

In distinguishing between the theoretical and technical scenarios, the most obvious difference is in the amount of feces and urine used as input material for the nitrogen recycling. In the theoretical scenario, both liquid fertilizer and humus fertilizer yield are about ten times higher than in the technical scenario. However, as shown in Figure 4-7 and Figure 4-8, humus fertilizer is relatively marginal in the overall fertilizer input. Even with a tenfold increase, humus fertilizer represents less than 1 % of the nitrogen fertilizer input in both scenarios. In contrast to feces, changes in urine inputs can dramatically affect the proportion of nitrogen in the total fertilizer input. Liquid fertilizer can account for 12.7 % of the total nitrogen input in the crop production (metabolism demand & fertilizers & straw for humus) when all of the urine in the area is reused, and only 1.4 % when only a fraction of the urine is recovered.

The distribution in the total N inputs of the various fertilizers remained generally consistent when comparing the technical scenario with the future sustainable scenario. In the future sustainable model, the proportion of manure utilized directly decreased by 8.1 % due to a reduction in the number of cattle. In addition, the utilization of sewage sludge by agriculture changes slightly. Nitrogen obtained from this source decreases from 2.1 % to 0.5 %, suggesting that the amount of sewage sludge used directly for agricultural activities will decrease within the scope of the new legislative measures.

However, it is important to emphasize that the projected use of sewage sludge for agriculture presupposes the expected capacity of the current central sewage treatment plant. This assumption presupposes that all sludge from sewage treatment plants with a population of more than 10,000 residents will be treated for phosphorus recovery. However, according to Sewage Sludge Ordinance (AbfKlärV) phosphorus recovery is mandatory when the phosphorus concentration of sewage sludge exceeds 20 grams per kilogram of dry matter. In practical terms, therefore, the amount of sewage sludge affected by the new legislation is likely to be less than that envisaged in the future, which depicts a scenario of minimized sewage sludge utilization.

Figure 5-2 presents a comparison of the changes in nitrogen input flows for crop production across different scenarios. Notably, there's a significant increase in the nitrogen stock in the soil under the theoretical scenario. Conversely, the future scenario depicts a decline. Any input flows not illustrated in the figure remain unchanged in value.



	Ntot input in crop production	Ntot input from fertilizer	Sludge as fertilizer for agriculture	Fertilizer for agriculture and forestry (OFMSW)	N stock change	Manure (direct use)
■ Future	-2%	-2%	-79%	-4%	-91%	-8%
■ Technical	1%	2%	-7%	-1%	39%	0%
■ Theoretical	14%	19%	-25%	-5%	462%	0%

Figure 5-2 Summary of nitrogen content change in crop production in comparison to baseline scenario 2020 under different scenarios

5.2. Sensitivity analysis

5.2.1. Critical flows selection

A sensitivity analysis was conducted for the 2016 and 2020 baseline scenarios in order to assess the importance of specific flows to the overall model configuration. In the scenario study, the models are evolved from baseline scenario 2020. Additionally, with the introduction of the baseline thermophilic composting plant, changing the input to the plant in various scenarios can also be seen as a form of sensitivity analysis. Thus, the general sensitivity analysis based on the models from scenario study is not conducted here. In the end, eight different flows were selected for this analysis, as detailed in Table 5-1. The adjustments are made due to the uncertainty in the flows (see chapter 3.4).

Table 5-1 List of critical flows and their corresponding adjustments for Sensitivity Analysis

1.	Mineral fertilizer input	Mineral fertilizer input (E4) ± 15 %
2.	Mineral fertilizer application loss	N emission (J2) from mineral fertilizer application can range from 20 % - 80 %. (Baseline 50 %)
3.	Fertilizer for crop production of OFMSW section	Fertilizer (OFMSW) for crop production (D1) ± 15 %,
4.	Intercrop as green fertilizer	Intercrop as green fertilizer (F2) ± 50 %
5.	Forage	Forage input (L1) ± 50 %
6.	Humus return on field	Humus = 0.5 Technical straw potential (0.1 for Baseline)
7.	Manure direct use	Manure (direct use) (G2) ± 30 %
8.	Digestate	Digestate (G1) ± 30 %

By varying the values of these eight flows, the main focus was to understand their impact on changes in nitrogen stocks in the crop production cycle, which represents the nitrogen status in the field. Subsequently, the nitrogen stock changes were normalized to the cultivation area in Barnim for those two years, as a key parameter to illustrate the level of nitrogen excess.

In 2016, the change in nitrogen (N) stocks was 441.3 tons, resulting in a surplus of 9.8 kg N per hectare per year in soil. In contrast, by 2020, the change in N stocks decreases to 80.8 tons, resulting in a surplus of 1.9 tons N per hectare per year in soil. At first glance, this decrease can be attributed to the reduction of mineral fertilizer inputs in 2020. Therefore, mineral fertilizers were identified as critical flows. In addition, estimating N losses during mineral fertilizer application is challenging because their variability depends on a number of factors: regional conditions (e.g., temperature, humidity, rainfall, and soil type), application methods (timing, quantity, possible over-application), and the presence of urease inhibitors (Misselbrook et al. 2019). Nitrogen losses through gas emissions and leaching can vary considerably. Therefore, losses during mineral fertilizer application were also included in the sensitivity analysis.

Intercropping crops is another potential cause of modeling inconsistencies. Because data were limited to summer 2015, winter 2016, and summer 2019 and winter 2020, yields from intercrops may not properly reflect yields from intercrops throughout 2016 and 2020. There are also no data on the yield distribution of intercrops for green fertilizer and for forage in winter. It is assumed that the ratios for summer also apply to winter, suggesting that the assumed green fertilizer may be an important factor influencing nitrogen stock change.

There is a considerable degree of uncertainty in estimating forage requirements. Ideally, forage calculations should be based on the age and live weight of the animal. However, due to the unavailability of this important information, the estimates in this study are relatively generalized. It is important to consider how forage affects nitrogen conditions in crop production.

Fertilizers from the organic fraction of municipal solid waste (OFMSW), direct-use manure, and digestate were also selected for the sensitivity analysis, largely due to the lack of regional data for Barnim. The data acquisition relies on the corresponding proportions in the Land Brandenburg. Finally, humus return is expected to be 10 % of the technical potential of straw. In reality, this percentage may be higher. Therefore, in the sensitivity analysis, this proportion was adjusted to 50 %.

5.2.2. Result

In the 2016 baseline scenario, the most significant impact on flows is the change in nitrogen loss during the application of mineral fertilizers, with a deviation of ± 205 %. Increased nitrogen losses even lead to a negative change in nitrogen stocks, down to 10 t N/ha/a. The subsequent sensitive change is the input of mineral fertilizers, which shows that a complete cessation of the use of mineral fertilizers is still not feasible. This is then followed by deviations of ± 48 % and ± 41 % for digestate and direct use of manure, respectively. As shown in Table 5-2, even with reduced inputs of digestate or manure, soils in Barnim still have a N surplus.

The use of intercrops as fertilizers had a slight effect on the change in nitrogen stocks with a deviation of ± 14 %. Fertilizers derived from the organic fraction of municipal solid waste (OFMSW) had the least effect on crops with a deviation of only 1 %. Changes in forage requirements had little effect on changes in soil N stocks. However, adjustments in forage demand affect the total inputs and outputs of the system. An increase in forage demand requires an increase in imported forage and forage from the crop production sector. As a result, total crop products for output also decreases.

Table 5-2 Sensitivity analysis result of Baseline 2016

Critical flow	Mineral fertilizer input	Mineral fertilizer loss	Fertilizer (OFMSW) for crop	Intercrop as green fertilizer	Forage	Humus	Manure (direct use)	Digestate
Max								
N stock change (t)	667.81	1347.76	446.07	504.46	441.28	503.11	624.29	653.47
N stock change (t/ha/a)	14.8	29.8	9.9	11.1	9.8	11.1	13.8	14.4
Deviation	51%	205%	1%	14%	0%	14%	41%	48%
Min								
N stock change (t)	214.51	-465.44	435.85	378.1	441.28	/	258.16	229.12
N stock change (t/ha/a)	4.7	-10.3	9.6	8.4	9.8		5.7	5.1
Deviation	-51%	-205%	-1%	-14%	0%		-41%	-48%

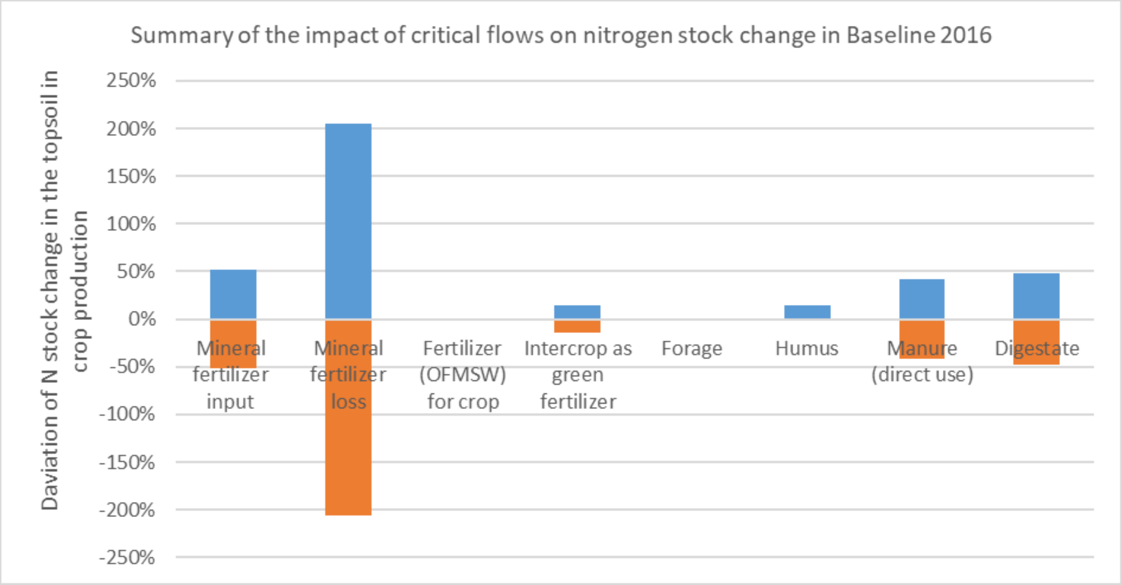


Figure 5-3 Summary of the impact of critical flows on nitrogen stock change in Baseline 2016

In 2020, the overall impacts of each flow remain generally consistent with 2016 (as presented in Figure 5-4 and Figure 5-5). However, due to the initially low N stock changes in 2020, the impacts are more apparent than in 2016 for all flows except forage. The most pronounced deviation is once again related to nitrogen loss during mineral fertilizer application, which reaches a staggering ± 630 %. This suggests that even small changes in N inputs can lead to significant changes in N stocks.

As shown in Table 5-3, by reducing the flow values of mineral fertilizers, direct-use manure, and digestate to their respective lower limits, while maximizing nitrogen losses during mineral fertilizer application, the soils of Barnim consistently reflected negative nitrogen stock changes to - 1.1 t N/ha/a, - 1.1 t N/ha/a , - 1.3 t N/ha/a and - 10 t N/ha/a, respectively. Consistent with the results of the 2016 study, changes in forage did not directly affect nitrogen stock.

Table 5-3 Sensitivity analysis result of baseline 2020

Critical flow	Mineral fertilizer input	Mineral fertilizer loss	Fertilizer (OFMSW) for crop	Intercrop as green fertilizer	Forage	Humus	Manure (direct use)	Digestate
Max								
N stock change (t)	207.77	589.2	87.9	131.43	80.76	138.36	207.71	303.84
N stock change (t/ha/a)	4.9	13.8	2.1	3.1	1.9	3.2	4.9	7.1
Deviation	157%	630%	9%	63%	0%	71%	157%	276%
Min								
N stock change (t)	-46.26	-427.2	73.5	30.09	80.76		-46.19	-142.33
N stock change (t/ha/a)	-1.1	-10.0	1.7	0.7	1.9	/	-1.1	-3.3
Deviation	-157%	-629%	-9%	-63%	0%		-157%	-276%

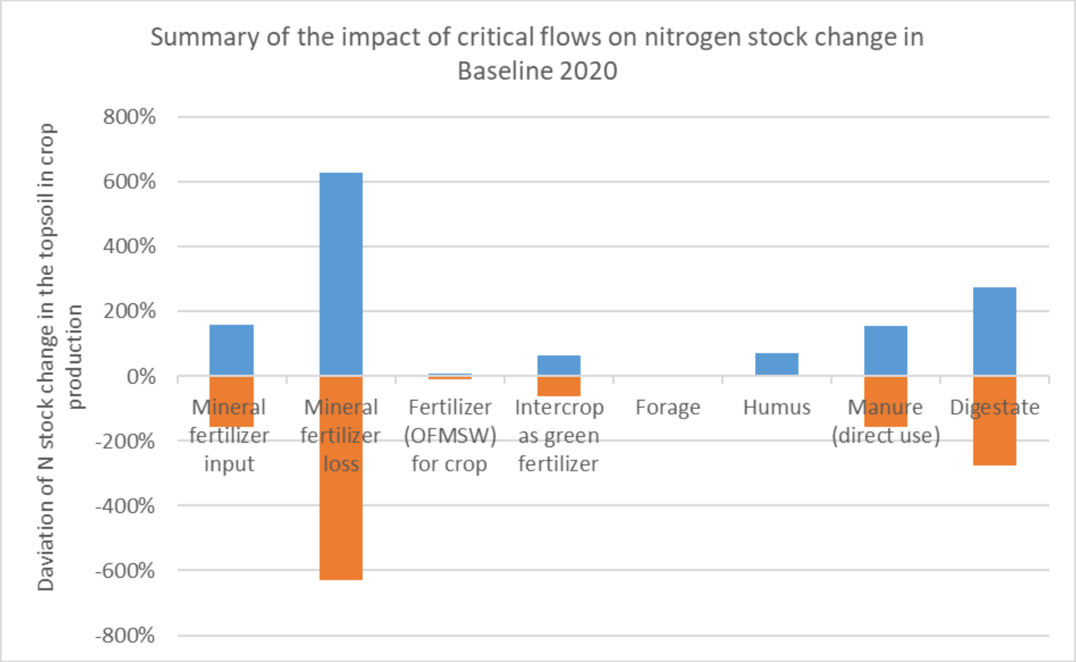


Figure 5-4 Summary of the impact of critical flows on nitrogen stock change in Baseline 2020

In summary, N stocks in soils are profoundly affected by mineral fertilizer flows and their associated losses during agricultural fertilization. Notably, the 2020 model is more sensitive to these critical flows compared to the 2016 model.

5.3. Nitrogen recovery potential and mineral fertilizer substitution potential in crop production

5.3.1. Nitrogen recovery rate

In this study, the nitrogen recovery of organic fertilizer from municipal resources is determined by the proportion of nitrogen reused in crop production relative to the N sourced from the input. It is interesting to investigate the role that inhabitants play in incorporating recycled fertilizers into agricultural practices, particularly through the sewage sludge and the biowaste they generate. This category of "other fertilizers" includes sewage sludge, fertilizers derived from biowaste, and green waste. In addition, liquid fertilizers and humus fertilizers are taken into account in the case of theoretical scenario, technical scenario and future sustainable scenario.

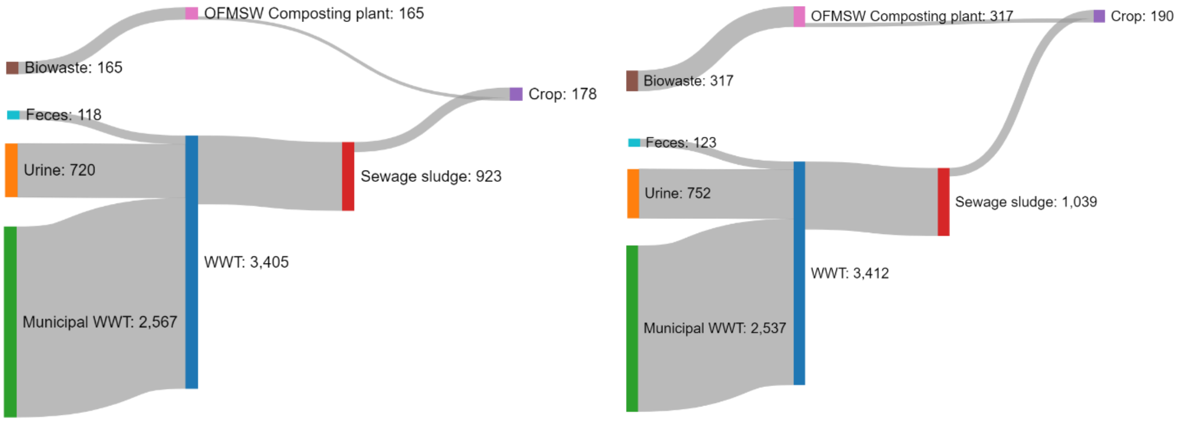


Figure 5-5 : The mass (in tons) of total nitrogen encompassed within various organic fertilizer production chains, from raw material acquisition to end-use in crop production, during the year 2016 (Left) and 2020 (Right)

Figure 5-5 illustrates the flow of total nitrogen from the feedstock state to its use as fertilizer for crop production in 2016 and 2020. In 2016, 178 tons of nitrogen extracted from municipal organic fertilizers was reintroduced into the agricultural sector. Of this, 43 tons of nitrogen was recovered from OFMSW and 135 tons came from human excreta and wastewater. Thus, in the 2016 scenario, nitrogen recovery from OFMSW was 25.9 % and 3.1 % from human excreta and wastewater. Compared to 2020, 190 tons of nitrogen from municipal organic fertilizers are recycled for agriculture. This reflects a comparable rate of nitrogen recovery from municipal wastewater. However, a notable decrease in nitrogen recovery from OFMSW biowaste was observed, from 25.9 % to 18.9 %, with an increase in nitrogen losses through the biowaste composting plant.

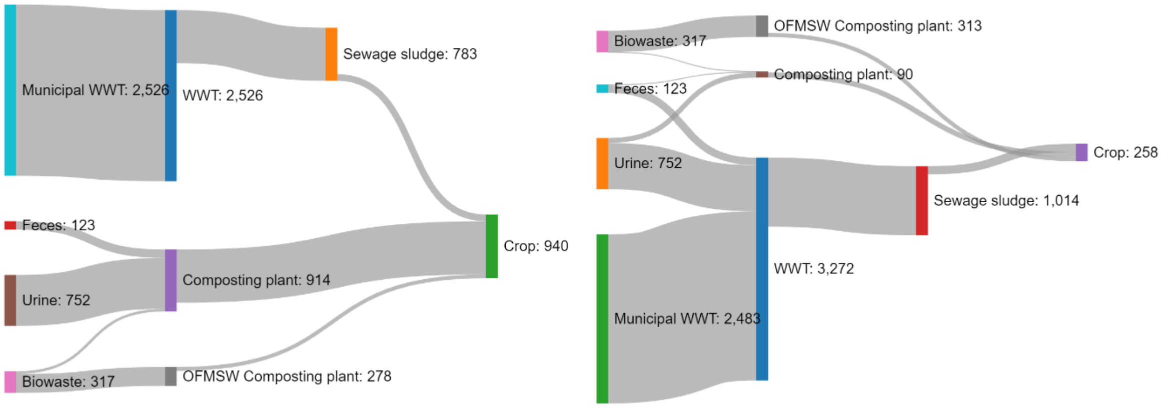


Figure 5-6: The mass (in tons) of total nitrogen encompassed within various organic fertilizer production chains, from raw material acquisition to end-use in crop production, from the theoretical scenario (Left) and the technical scenario (Right)

The scenario study showed that separate treatment of human urine and feces has the potential to improve nitrogen recovery. In the theoretical and technical scenarios, 940 and 258 tons of N were recovered from organic fertilizers for crop production, respectively. As shown in Figure 5-6, in the theoretical scenario, 98 tons of nitrogen were recovered from sewage sludge, 785 tons from recycled fertilizers, and 57 tons from the organic fraction of municipal solid waste composting plant for agricultural production. These figures show that nitrogen recovery from human excreta can be increased from 3.1 % (without specialized recycling treatment) to 20.9 %. The nitrogen recovery rate for OFMSW stays at 20.5 %. In the technical scenario, a significant portion of urine and feces is still treated in the wastewater treatment plant (WWTP), resulting in 121 tons of nitrogen in the sewage sludge and only 77 tons of nitrogen in the human excreta composting facility. Nitrogen recovery from human excreta in this scenario increased slightly to 4.5 % compared to the baseline. In addition, 60 tons of nitrogen was recovered from OFMSW waste for agricultural use, a nitrogen recovery rate of 19 %.

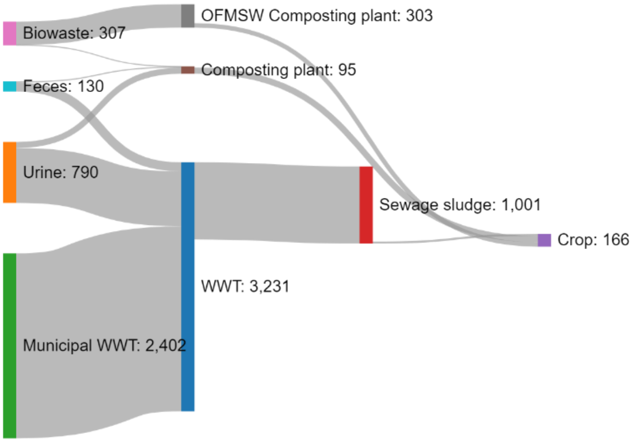


Figure 5-7 The mass (in tons) of total nitrogen encompassed within various organic fertilizer production chains, from raw material acquisition to end-use in crop production, from the future scenario.

In the future sustainable scenario, only 166 tons of nitrogen are recovered from municipal organic waste. As shown in Figure 5-7, a large portion of sewage sludge is not recovered for use as fertilizer. Meanwhile, the recovery rate through OFMSW was 19 %. As a result, this scenario has the lowest nitrogen recovery rate of municipal organic fertilizer among the three scenarios, at 2.5 %.

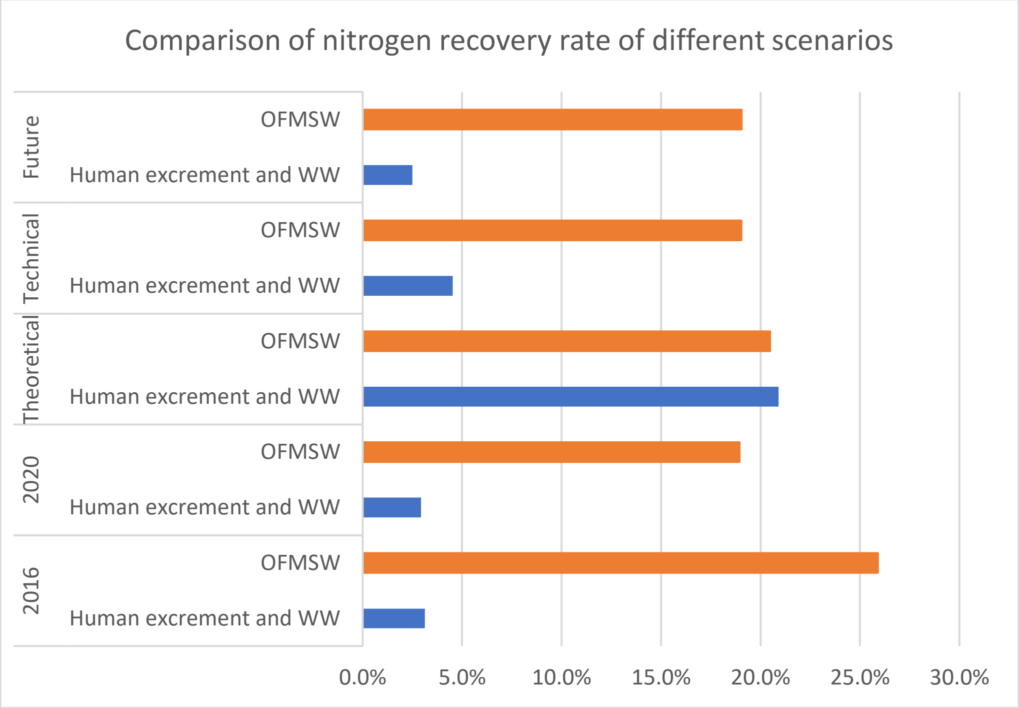


Figure 5-8 Comparison of nitrogen recovery rate of different scenarios

Figure 5-8 provides an overview of nitrogen recovery from OFMSW waste and human excreta under five scenarios. The theoretical scenario has the highest recovery rates, while the future scenario has the lowest. Table 5-4 provides a comprehensive summary of nitrogen recovery rates of urban organic fertilizers in general.

Table 5-4 Summary of total nitrogen recovery rate from municipal organic fertilizer

Scenario	Recovery rate
Baseline scenario 2016	5.0 %
Baseline scenario 2020	5.1 %
Theoretical scenario	24.7 %
Technical scenario	7.0 %
Future sustainable scenario	4.5 %

Furthermore, in this study, the focus of the recovery rate is on the nitrogen recovered and utilized in the agricultural sector. However, it is important to understand that the unrecovered nitrogen does not necessarily mean that it is lost during processing. For example, when considering all fertilizers in the OFMSW segment, regardless of their intended use, the nitrogen recovery rates under the 2016 Baseline, 2020 Baseline, Theoretical, Technical, and Future Scenarios increase to 47 %, 31 %, 33 %, 31 %, and 31 %, respectively. Conversely, while the future sustainable scenarios indicates low nitrogen recovery, it is important to emphasize that any sewage sludge that is not suitable for agricultural use will go through a phosphorus recovery process, which has the potential to increase phosphorus recovery.

5.3.2. Mineral fertilizer substitution potential

Both humus and liquid fertilizers are viable alternatives to mineral fertilizers for crop production, and can be considered as substitutes for mineral fertilizer. The potential for substitution can be calculated using the 2020 baseline nitrogen reserve surplus as a benchmark. Table 5-5 shows the result of the substitution potential while Table 5-6 shows the result of the maximum substitution potential.

Table 5-5 Summary of mineral fertilizer substitution potential from different scenarios

	Theoretical	Technical	Future sustainable
Mineral fertilizer input without reduction (t N)	1694	1694	1694
Mineral fertilizer reduction (t N)	746	64	-147
Mineral fertilizer input after reduction (t N)	947	1630	1841
Substitution potential (%)	44.1%	3.8%	-8.7%

The theoretical scenario shows the greatest potential for substitution, saving 746 tons of nitrogen from mineral fertilizers. This indicates that recycled fertilizers derived from human excreta could replace 44.1 % of mineral fertilizers. In the technical scenario, the substitution potential of recycled fertilizers is 3.8 %, which could reduce 64 tons nitrogen from mineral fertilizers. However, the results from the future sustainable scenario are markedly different. Given that the original nitrogen surplus in this future scenario is already lower than that of the baseline 2020, there is no potential for reducing Mineral fertilizer use. Furthermore, to achieve the same nitrogen surplus as in 2020, an additional 147 tons of nitrogen would be required.

Table 5-6 Summary of maximum mineral fertilizer reduction potential from different scenarios

	Theoretical	**Technical**	**Future sustainable**
Mineral fertilizer input without reduction (t N)	1694	1694	1694
Mineral fertilizer reduction (t N)	908	225	14
Mineral fertilizer input after reduction (t N)	786	1468	1679
Substitution potential (%)	53.6%	13.3%	0.8%

In addition, the maximum potential for reducing mineral fertilizers is revealed when the nitrogen surplus is netted off. This means that the nitrogen from total input is equal to the sum of crop and straw yield and nitrogen losses. Ideally, a theoretical reduction of 53.6 % of mineral fertilizer could be achieved, i.e. a saving of 908 tons of nitrogen from Mineral fertilizer. Thus, the amount of mineral fertilizer required is only 30 % of the original input. In the technical scenario, it is possible to reduce the input of nitrogen by 225 tons, which corresponds to a reduction of 13.3 % of the mineral fertilizer. In the future scenario, it is possible to reduce nitrogen extraction from mineral fertilizers by 0.8 %, resulting in a saving of 14 tons of nitrogen.

Figure 5-9 shows new nitrogen share from different fertilizers with the maximum reduction of mineral fertilizer. Of the three scenarios, the future sustainable scenario currently has the highest amount of fertilizer nitrogen inputs. However, the difference in total nitrogen input between the three scenarios is not significant. In the theoretical scenario, nitrogen from mineral fertilizers accounts for only 21 % of the total. Similar decreases in nitrogen content occur in the Technology Scenario and the Future Scenario, with 34 % and 43 %, respectively.

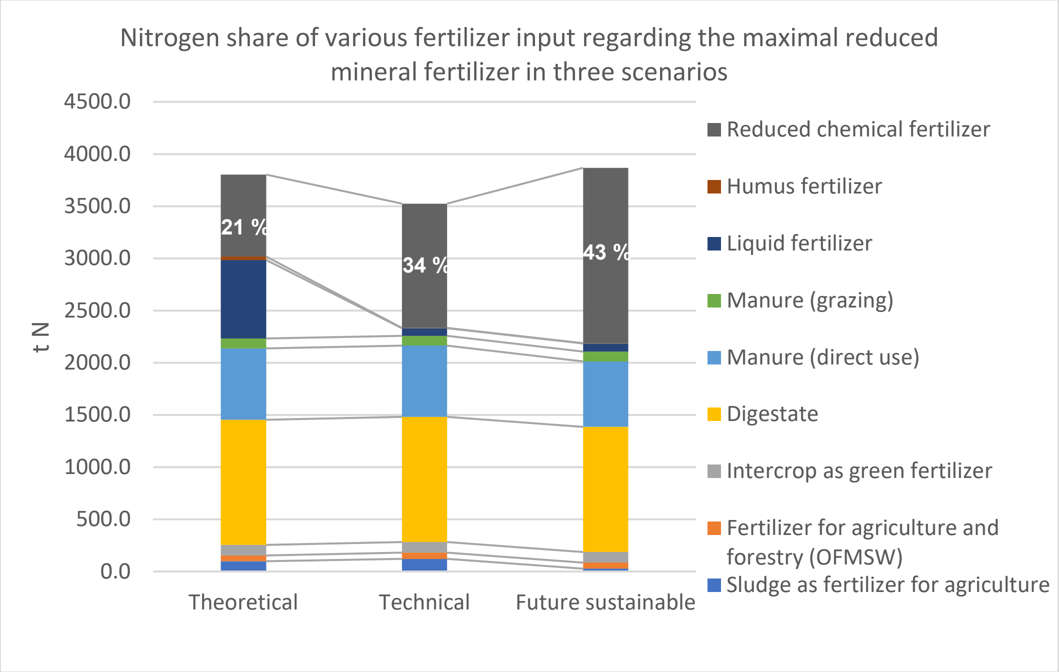


Figure 5-9 Nitrogen share of various fertilizer input regarding the maximal reduced mineral fertilizer in three scenarios

Nevertheless, the substitution and reduction potentials are based on statistical calculations. The nitrogen use efficiency (NUE) of mineral fertilizers and compost is significantly different. Typically, the NUE of mineral fertilizers ranges from 40 % to 80 %, while that of compost is limited to 0-30 % (Guster et al. 2010). A higher NUE indicates that N fertilizers are more effective soon after application. This suggests that for the same N input from mineral fertilizers and compost, compost will be less effective for plants in a short period of time. This dynamic may lead to a decrease in yield.

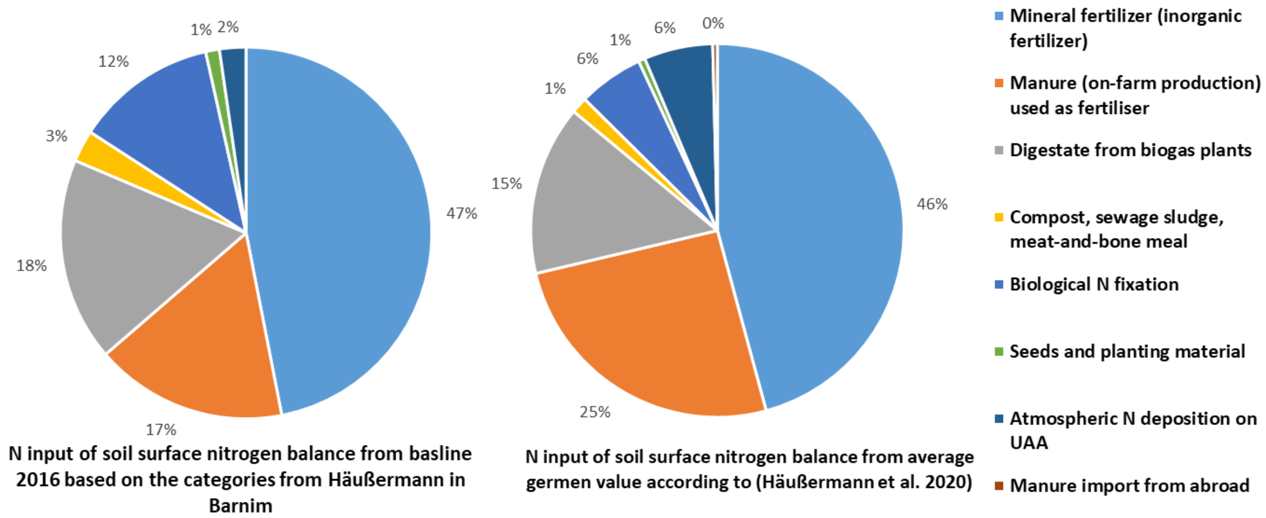
5.4. Nitrogen stock change in agricultural sector and literature value

Table 5-7 Summary of nitrogen stock change in soil from 5 scenarios with the comparison to average value in Germany

	Baseline 2016	Baseline 2020	Theoretical scenario	Technical scenario	Future sustainable scenario	Germany, mean 2015-2017, (Häußermann et al, 2020)
Nitrogen stock change (kg N/a)	441.3	80.8	453.9	112.6	7.2	
Nitrogen stock change (kg N/ha/a)	9.8	1.9	10.6	2.6	0.2	77.4

According to (Häußermann et al. 2020), the average N budget surplus in the soil surface from crop production was 77.4 kg N/ha/a during the period 2015-2017. This figure is considerably higher than the change in N reserves calculated in 2016 baseline scenario (see Table 5-7). The reason for this discrepancy is that (Häußermann et al. 2020) only considered NH_3 emissions from fertilization in the soil N balance output. Thus, the nitrogen surplus in soil symbolizes the potential for N loss from the soil to the atmosphere and hydrosphere. In contrast, the present study included potential gaseous N losses (e.g., NH_3, N_2O, and N_2) as well as losses from leachate and runoff. As a result, the total N loss from crop production assumed in this study is much higher compared to what has been reported in the literature.

To facilitate a uniform comparison, the data from this study have been organized according to the description of (Häußermann et al. 2020) , and the comparative values are shown in Table 5-8. If only NH_3 emissions from fertilizer application are considered, the budget surplus for the 2016 baseline is then 35.4 kg N/ha/a in Barnim region. This value is consistent with the range of 26-60 kg N/ha/a depicted in Figure 3 in (Häußermann et al. 2020). In addition, all five scenarios result in budget surpluses that are consistently lower than the average budget surplus recorded in Germany during the 2015-2017 period. It is worth noting that when looking at all input streams, the total nitrogen inputs to the crop production section in Barnim region are lower than the average inputs to Germany in the period 2015-2017.



N input of soil surface nitrogen balance from basline 2016 based on the categories from Häußermann in Barnim

N input of soil surface nitrogen balance from average germen value according to (Häußermann et al. 2020)

Figure 5-10 Comparison of N input of soil surface nitrogen balance between baseline scenario 2016 and literature

When comparing the results of the 2016 baseline scenario in this study with the 2015-2017 mean value of Germany, it is clear that mineral fertilizers account for a comparable share of overall inputs (see Figure 5-10). Specifically, almost half of the nitrogen inputs in crop production are sustained through the use of mineral fertilizers. In contrast, in the Barnim region, the contribution of manure fertilizer is more limited compared to the German average. According to (Häußermann et al. 2020), Barnim region is not characterized by intensive livestock farming. Furthermore, Table 5-8 shows that the nitrogen budget surplus in the Barnim region is expected to decline in the coming years.

Table 5-8 Comparison of the N soil surface budget

t N /ha	Baseline 2016	Baseline 2020	Theoretical scenario	Technical scenario	Future sustainable scenario	Germany, mean 2015-2017, (Häußermann et al, 2020)	Barnim, mean 2015-2017,(Häußermann et al, 2020)
Input total	**142.3**	**118.1**	**137.8**	**119.9**	**116.4**	**226.5**	
Mineral fertilizer (inorganic fertilizer)	66.8	39.7	39.7	39.7	39.7	103.7	
Manure (on-farm production) used as fertiliser	23.8	18.2	18.2	18.2	16.9	57.8	
Manure import from abroad	NA	NA	NA	NA	NA	0.9	
Digestate from biogas plants	25.2	28.1	28.1	28.1	28.1	33.3	
Compost, sewage sludge, meat-and-bone meal	3.9	4.5	24.2	6.3	4.1	3.2	
Biological N fixation	17.6	21.8	21.8	21.8	21.8	12.8	
Seeds and planting material	1.7	1.8	1.8	1.8	1.8	1.3	
Atmospheric N deposition on UAA	3.3	3.8	3.8	3.8	3.8	13.5	
Output total	**107.0**	**97.2**	**101.6**	**97.6**	**97.3**	**149.0**	
Harvest withdrawal of crop and straw	81.1	78.6	78.6	78.6	78.6	125	
Harvest withdrawal of energy plants for biogas	0	0	0	0	0	18.6	
NH3 emissions from fertiliser application	25.9	18.6	23.0	19.0	18.8	5.4	
Budget surplus	**35.4**	**20.9**	**36.2**	**22.3**	**19.1**	**77.4**	**26-60**

5.5. Evaluation and suggestions.

5.5.1. Data evaluation

A major limitation of this study is the accessibility and consistency of the data. Most of the available data are consistent with data available at the federal state or national level in Germany. Many key data points, such as those related to mineral fertilizer utilization, cannot be obtained directly from the statistical source, but need to be estimated based on the proportions of the state of Brandenburg. According to (Häußermann et al. 2020), the only ways to estimate mineral fertilizer use are through assessing the demand for fertilizer by crops or estimating it from fertilizer purchases. However, these methods don't accurately represent the actual amount of chemical fertilizer applied to the fields. It is important to either conduct a survey to understand the usage of chemical fertilizer in different regions or develop a model to predict chemical fertilizer usage based on various parameters.

In the case of fertilizers from OFMSW, for example, values were estimated with reference to statistical data on biological treatment plants and the subsequent utilization of the resulting compost or digestate. These values are mainly set in the context of the Brandenburg region. Preliminary studies have shown that Barnim does not have a central biogas plant dedicated to the treatment of municipal biowaste. Therefore, estimates of fertilizer production were derived based on the population ratio of Barnim to Brandenburg, multiplied by the fertilizer production of the biowaste and green waste composting plants. However, the actual figures may be biased, thus introducing potential inaccuracies into this study.

A further challenge in data acquisition is the lack of granular information. For example, while data on livestock numbers are available for specific dates throughout the year in the Barnim area, detailed information on the age and live weight of livestock is needed to effectively estimate forage requirements. In addition, to accurately estimate overall livestock flows on farms, it is also necessary to know the number of animals purchased during the year, the number of animals utilized for meat production through slaughter, and the number of animals that died due to disease. Without access to this comprehensive information, livestock-related estimates are necessarily broad, which introduces a large degree of uncertainty into the study.

In terms of consistency, the limitations of data sources pose a challenge. The data were obtained by a variety of methods: directly from statistical data, extrapolated from German data, determined by scaling, referred to general international data, through rough assumptions, and derived from experimental results. This amalgamation resulted in serious inconsistencies in the data. In addition, the results of the sensitivity analyses indicate that factors such as fertilizer application losses, mineral fertilizer digestate and manure can have a profound impact on the system. However, data for these factors were largely derived from scaling calculations or assumptions, further amplifying uncertainties.

Furthermore, this study discovered that analyzing material flow at the agricultural level is more challenging compared to substance flow (like nitrogen flow). This is because estimating the mass loss in a field within a year is impossible. Therefore, it's suggested that future studies should focus on specific substances of interest rather than analyzing all the materials in a region related to agriculture, as this approach would be more meaningful and manageable.

To avoid these difficulties in future mass flow studies focusing on smaller regions (e.g., individual farms or communities), it is preferable to use a bottom-up approach rather than a top-down approach. For larger regions (e.g. federal states or countries), statistical data may be more available. For future nitrogen flow analyses at the county (Landkreis) level or above, the study by (Häußermann et al. 2020) can be consulted. For more detailed nitrogen flow analyses, the methodology provided by (Coppens et al. 2016) is a valuable resource.

5.5.2. Recycled fertilizer from human excreta

As described in Chapter 5.3, recycled fertilizers have the potential to replace mineral fertilizers with up to 54 % of potential nitrogen. However, this impressive potential is mainly observed in theoretical scenario. This means that this result can only be achieved if every household uses dry toilets and regularly transports the collected feces and urine to a specialized treatment facility. Implementing such a system in densely populated urban areas or in established buildings is a great challenge. In addition, there is a general concern about the introduction of dry toilets in household, mainly due to the fear of possible odors.

From a technical point of view, 13 % of mineral fertilizers are likely to be replaced in 2020, while in future scenario, this figure will drop to 1 %. In these cases, composting dry toilets can be introduced pragmatically in areas where the population mainly has access to small wastewater treatment or collection pits. However, with the current handling capacity, 78 urine treatment facilities and 15 feces composting plants will be needed to achieve the provisions in the 2020 technical scenario. By 2030, these needs are projected to increase to 82 urine treatment facilities and 16 feces composting facilities. This surge implies significant infrastructure requirements. If these plants increase their capacity, this will inevitably lead to greater centralization, which will increase transportation costs and logistical complexity.

In contrast, the Barnim region remains significantly dependent on mineral fertilizers, whose demand and application remain critical. One potential way to reduce mineral fertilizer inputs is to reduce nitrogen loss during application. Several methods proposed by (Misselbrook et al. 2019), such as replacing urea with other types of fertilizers, and using urease or nitrification inhibitors, could significantly reduce nitrogen loss during mineral fertilizer application.

In general, humus fertilizer is recognized for its greater stability and lower environmental impact. However, the production of humus fertilizer is evidently limited. The feasibility of producing humus fertilizer on a large scale and bringing it to market deserves further study. At the same time, decentralized methods of manure and urine treatment may be more practical than centralized systems due to the lower infrastructure requirements associated. Feces and urine can be efficiently collected and treated on-site in smaller communities. After a humification and purification process, the final humus and liquid fertilizer can be reused directly on household plants or in backyard gardens. AnEco's dry toilet technology has been adopted by the Equilibre Cooperative Household in Confingon, Switzerland (AnEco 2022). Human urine and feces are collected separately in the basement of the building. The feces are then vermicomposted, a technique that is particularly suited to small residential buildings, which can house up to 45 residents (AnEco 2022). The residents then use the humus fertilizer in their own gardens, thereby reducing reliance on commercial fertilizers for domestic use.

In conclusion, recycled humus fertilizers from Barnim have the potential to replace mineral fertilizers and be reintegrated into agriculture. However, a comprehensive feasibility study is necessary to validate this approach. Future studies could also delve into the potential for nitrogen recycling in fertilizer for private households.

6. Discussion and future outlook

An in-depth study of nitrogen and material flows is essential to determine the prospects for nitrogen recovery and reuse from human excreta in the Barnim region. Barnim is located in the state of Brandenburg, which is among the regions with a low level of overnutrition compared to the German national average, mainly due to the low intensity of livestock production. As a result, the nitrogen excess in the topsoil of agricultural fields is significantly lower than the German average, which highlights the need for efficient fertilization.

The agricultural sector is the main conduit for nitrogen flux in the region, as evidenced by the large amount of harvested crops that are removed from the fields. Large quantities of mineral fertilizers are spread over the arable land in Barnim, increasing fertilizer application losses to the environment. These emissions, together with the use of chemical fertilizers and manure application, have been identified as sensitive fluxes in the system that have a significant impact on the nitrogen excess in the soil, thus emphasizing the need to strengthen the implementation of low-emission fertilizer application strategies along with the assessment of soil nutrient stocks in cropland. While mineral fertilizers represent a large proportion of fertilizer inputs, a trajectory of decreasing mineral fertilizer inputs is clearly visible in Barnim, with mineral fertilizer inputs in 2020 set to be almost half of what they were in 2016. This trend reflects a broader shift towards a more ecologically sustainable model of agriculture, which puts nitrogen stocks in cropland in a positive state.

In addition, the accomplishment of a pilot facility specializing in the thermophilic treatment of human excreta opens up new prospects for replacing mineral fertilizers with recycled fertilizer in the Barnim region. Theoretically, the region has great potential for transitioning to recycled fertilizers made from human excreta, a prospect that was further clarified by a scenario analysis that assumed a significant decline in dependence on mineral fertilizers if urine and feces from Barnim residents were fully collected. However, the infrastructural obstacles associated with the full replacement of flush toilets with dry toilet systems significantly reduce the potential for substitution. Nevertheless, the prospect of recycling fertilizers to catalyze changes in other parts of the system (e.g., private household nutrient demand) provides fertile ground for exploration.

In the future, the adoption of dry toilets may gain even more development due to the need to reduce the operational load on existing wastewater treatment facilities. Given the low population density of Barnim, the vast rural area is an ideal location for the installation of dry toilets. In addition, the abundance of outdoor activities and festivals in the region during the summer months offers great promise for piloting the use of human excreta for nutrient recycling, thus providing a valuable incentive for future research on its systemic impacts.

The regional case study presented in this study advances the theoretical potential of sustainable nitrogen management. However, the feasibility of deploying dry toilet systems on a large scale, and the necessity and safety of utilizing human excreta, need to be further investigated in order to advance the completion of legal framework related to recycled fertilizers produced from human excreta.

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Appendix A. Reference for flow calculations

A1 Household

Table (appendix) A-1 Overview on data sources in Block "Household"

Flow	Information[1]	Reference	Remark
A1-A6	A	[1][2]	Population, Population distribution analysis
A1-A6	M,N	[3]	Excrement and nitrogen generation
B1-B2	A	[9]	Municipality population distribution
B1-B5	M	[4]	Table (appendix) A-2
B1-B5	N	[5][6]	Table (appendix) A-3
H1	M	[7]	
H1	N	[8]	Require protein and nitrogen conversion
H4	M	[10]	

[1] Statistik Berlin Brandenburg, Bevölkerungsstand in Berlin und Brandenburg, https://www.statistik-berlin-brandenburg.de/

[2] MLUK: Kommunale Abwasserbeseitigung im Land Brandenburg – Lageberichte. https://mluk.brandenburg.de/mluk/de/ueber-uns/oeffentlichkeitsarbeit/veroeffentlichungen/detail/~22-06-2023-kommunale-abwasserbeseitigung-im-land-brandenburg-lageberichte#

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[6] Xin Liu, Yuancheng Xie, Hu Sheng 2023: Green waste characteristics and sustainable recycling options, Resources, Environment and Sustainability, Volume 11, 2023, 100098, ISSN 2666-9161, https://doi.org/10.1016/j.resenv.2022.100098.

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Table (appendix) A-2 Proportion of urban and rural residents in Barnim in 2016 and 2020

Year	2020	2016
Inhabitants (rural)	12 %	12 %
Inhabitants (urban)	88 %	88 %

Table (appendix) A-3 Characteristics of biowaste in urban and rural areas of Barnim

Waste type	Biobin (Rural area)		Biobin (Urban area)		Green Waste	
Parameters	DM (%FM)	N (%DM)	DM (%FM)	N (%DM)	DM (%FM)	N (%DM)
Mean	32.86	1.99	30.5	2.15	65.8	1
Reference	[5]				[6]	

A2 Agriculture - Crop production

Table (appendix) A-4 Overview on data sources in Block "Crop production"

Flow	Information	Source	Remark
E1	M	[11]	Sum of the products
E1, E2, H2	N	[12]	Sum of the nitrogen content
K1	M	[11] [12]	Crop * Product-Residue Rate* feasible collection rate (Table (appendix) A-5)
K1-K4	N	[12] [2]	
K2	M	[13]	
E5,F4	A	[15]	CO_2 (Table (appendix) A-6)

E5,F4	A	[19] [20]	[20] Nitrogen fixation; N supply with seed and planting material [19]N from deposition
E4	M,N	[16]	Extrapolated from the data of Brandenburg
J2	N	[17][18][21]	Table (appendix) A-7

[11] Statistik Berlin Brandenburg, Ernteberichterstattung über Feldfrüchte und Grünland im Land Brandenburg, C II2-j/16 &20, https://www.statistik-berlin-brandenburg.de/

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Table (appendix) A-5 Summary of the feasible collection ratio of straw

	Stubble height	Growth height	Feasible collection ratio	
	m	m	%	average
Wheat	0.1	0.5-1.5	80-93	0.865
Rye	0.1	1.5-2	93-95	0.94
Barley	0.1	0.7-1.2	86-92	0.89
Triticale	0.1	0.5-1.25	80-92	0.86
Oats	0.1	0.6-1.5	83-93	0.88

Table (appendix) A-6 Summary of Net Primary Production (NPP) of different types of crops

Crop type	NPP (tC/ha/yr)
Winter wheat incl. spelt and einkorn	7.2
Spring wheat	7.2
Rye and winter meslin	4.7
Triticale	5.5
Winter barley	6.1
Spring barley	4.8
Oats	5.8
Grain corn/corn for maturing (incl. corn-cob	10.4
silage corn/green corn (incl. timothy meal)	7.7
Legumes for whole crop harvest	5.3
Field grass/grass cultivation on arable land	5.7
Potatoes	5.4
Sugar beets without seed production	4.9
Peas (excluding fresh peas)	3.5
Sweet lupins	4.9
Winter rapeseed	6.8
Sunflowers	4.9
Meadows (mainly cut)	5.6
Pastures (incl. cut pastures)	5.6
Intercrop	4.9

Table (appendix) A-7 Summary of the emission rate of different fertilizers

Emission Rate	**Manure on grazing**	**Manure**	**Mineral fertilizer (urine)**	**Humus fertilizer**
F(NH_3)	8 %	19 %	N.A.	2 %
F(N_2O)	1 %	1 %		2 %
F(N_2)	8 %	8 %		
F(L&R&E)	10 %	10 %		20 %
Total loss rate	27 %	38 %	50 %	24 %
Reference	[17]	[17]	[21] & Estimation	[18]

A3 Agriculture - Livestock

Table (appendix) A-8 Overview on data sources in Block "Farm"

Flow	Information	Reference	Remark
L1,L3	M,N	[14] [32]~[48]	[14] Animal number [32]~[48] Fodder and water demand Summary of the fodder and water demand based on different animals can be found in Table (appendix) A-9
G1-G2	M	[22]	Extrapolated from the data of Brandenburg
G1-G2	N	[23]	
G3	M,N	[49][50]	Table (appendix) A-10 Grazing informationTable (appendix) A-10
L4	N	[25]	
L4	M	[12]	
G4	M	[34]~[36]	[34] Egg production; [35] Meat production; [36] Milk production Extrapolated from the data of Brandenburg
G4,G5,H3	N	[37]~[39]	[37] Egg; [38] Meat; [39] Milk

[22] Statistik Berlin Brandenburg, Wirtschaftsdünger im Land Brandenburg C IV 12 – u /16 & 20, https://www.statistik-berlin-brandenburg.de/

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[27] Statistik Berlin Brandenburg, Schlachtungen und Fleischerzeugung im Land Brandenburg C III 6 - m 01 /16 & 20, https://www.statistik-berlin-brandenburg.de/

[28] MSGIV 2023: Milch und Milcherzeugnisse. Milch und Milcherzeugnisse https://msgiv.brandenburg.de/msgiv/de/themen/verbraucherschutz/lebensmittelueberwachung/milch-und-milcherzeugnisse/#. checked on 10/29/2023

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[30] Analytical Methods Committee Amctb No. Meat and poultry nitrogen factors. Anal Methods. 2014 Jun 12;6(13):4493-4495. doi: 10.1039/c4ay90043j. PMID: 33985307.

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Table (appendix) A-9 Fodder and water demand (chosen value) and reference

	Feeding demand	**Ref.**	**Crude protein**	**Ref.**	**Water demand**	**Ref.**
Unit	**kg/cap/d**		**g/cap/d**		**l/d**	
Milking cows	Calculation directly from the table	[32]	3000	[34]	80	[42]
Dry cows			1550		50	
Young cattle up to 1 year			650		20	
Young cattle 1 - 2 years			860		30	
Young cattle over 2 years			1090		40	
Piglets	1	[33]	170 (g/kg Feed)	[34]	7	[43]
Breeding sows	3.1		120 (g/kg Feed)		30	[44]
Other pigs	2.9		170 (g/kg Feed)		13	[43]
Sheep under 1 year	1.5	[34]	240	[34]	2.5	[43]
Ewes	2.4		330		7	

other sheep	1.8		220		6	
female goats for breeding	2.7		410		20	
other goats	1		95		10	
Equine	7.5	[35]	100 (g/kg Feed)	[39]	45	[43]
Chickens	0.12	[36]	170 (g/kg Feed)	[40]	0.25	[45]
Geese	0.2	[37]	200 (g/kg Feed)	[37]	1.5	[46]
Ducks	0.185	[38]	200 (g/kg Feed)	[41]	1	[47]
Turkeys	0.2	[37]	200 (g/kg Feed)	[37]	2	[48]

[32] LfL 2023: Rationsberechnung Rindermast und Jungvieh,https://www.lfl.bayern.de/ite/rind/024444/index.php, checked on 10/29/2023

[33] LfL 2021a: Futterberechnung für Schweine. https://www.lfl.bayern.de/mam/cms07/publikationen/daten/informationen/futterwerttabelle_schwein_lfl-information.pdf, checked on 10/29/2023

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[36] Landbauforschung 2018: vTI Agriculture and Forestry Research, Sonderheft 322 / Special Issue 322 (2008). https://literatur.thuenen.de/digbib_extern/dk041076.pdf .checked on 10/29/2023

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[44] Bayerisches Landwirtschaftliches Wochenblatt, 1. Feb. 2008, Heft 5, S. 32-33. checked on 10/29/2023

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Table (appendix) A-10 Grazing information

Animal type	Gazing Rate	Reference
Milk cow	4 %	[49]
Other cattle	22.9 %	[49]
Pig	0 %	[49]
Sheep/goat	55 %	[50]
Horse	25 %	Estimation
Poultry	17 %	[49]

[49] Statistik Berlin Brandenburg 2021: Endgültige Ergebnisse der Landwirtschaftszählung 2020 Weniger Haltungsplätze für Rinder und Schweine in Brandenburg. https://www.statistik-berlin-brandenburg.de/187-2021 Checked on 10/29/2023

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A4 Agriculture - Intercropping

Table (appendix) A-11 Overview on data sources in Block "Intercropping"

Flow	**Information**	**Reference**	**Remark**
F2,F3	M,N	[51][52]	
F1	N	[53]	
F1	M	[23]	Assumed using manure

[51] Statistik Berlin Brandenburg, Zwischenfruchtanbau im Land Brandenburg, C I 9 – 3j / 16&19, https://www.statistik-berlin-brandenburg.de/

[52] LfL 2023b: Basisdaten (Düngeberatung/Düngerecht), Tabelle 1b: Nährstoffgehalte von Zweitfrüchten und Zwischenfrüchten (Stand: 27.06.2023). https://www.lfl.bayern.de/iab/duengung/031245/

[53] LfL 2007: integrierter Pflanzenbau Zwischenfruchtbau. https://www.lfl.bayern.de/mam/cms07/publikationen/daten/informationen/p_28819.pdf. checked on 10/29/2023

Table (appendix) A-12 Yield of intercrop and the fertilizer demand

Parameter	Units	Intercrop for		Reference
		green fertilizer	Forage	
Yield	dt/da	200	200	[52]
	gN/da	0.35	0.35	
Fertilizer demand	dt/da	0.02	0.04	[53]

A5 Waste management

Table (appendix) A-13 Overview on data sources in Block "Intercropping"

Flow	**Information**	**Reference**	**Remark**
D1-D3	M	[54]	Extrapolated from the data of Brandenburg
D1-D3	N	[55]	

I1,I2	M	[56]	
I1-I4	N	[57]	
I3,I4	M	[58]	
C2,C4	M	[59]	
C1-C4	N	[60][61][62][63]	Table (appendix) A-14

[54] Statistik Berlin Brandenburg, Abfallentsorgung im Land Brandenburg, Q II 1 - 2j / 16&20, https://www.statistik-berlin-brandenburg.de/

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[59] Statistik Berlin Brandenburg, Entsorgung von Klärschlamm im Land Brandenburg. Q I 9 - j / 17&20 https://www.statistik-berlin-brandenburg.de/

Table (appendix) A-14 Summary of nitrogen content in sewage sludge from different references

kgN/TS	Reference
36	[60]
48	[61]
34.9	[62]
44	[62]
43.64	[63]
44.4	Chosen value

[60] Umwelt Bundesamt 2018: Klärschlammentsorgung in der Bundesrepublik Deutschland. Fachgebiete III 2.4 – Abfalltechnik, Abfalltechniktransfer und III 2.5 – Überwachungsverfahren, Abwasserentsorgung.

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[61] Landwirtschaftskammer 2022: Mittlere Nährstoffgehalte organischer Dünger in der Frischmasse. https://www.landwirtschaftskammer.de/landwirtschaft/ackerbau.

[62] Ver- und Entsorgungsverband Adelebsen 2020: Abwasser - Klärschlamm als Düngemittel https://www.vev-adelebsen.de/abwasser/analysen-untersuchungen/index.html checked on 29/10/2023

[63] Bund für Umwelt und Naturschutz Deutschland 2005: BUNDposition Klärschlamm. https://www.bund.net/fileadmin/user_upload_bund/publikationen/bund/position/klaerschlamm_position.pdf checked on 29/10/2023

A6 Food production

Table (appendix) A-15 Overview on data sources in Block "Food production"

Flow	Information	Reference
H6	M	[64]
J6	M	[64]
J6	N	[65]

[64] Schmidt, Thomas; Schneider, Felicitas; Leverenz, Dominik; Hafner, Gerold (2019): Lebensmittelabfälle in Deutschland –Baseline 2015 –. 79 volumes. Thünen Rep 71. Available online at https://www.thuenen.de/media/publikationen/thuenen-report/Thuenen_Report_71.pdf.

[65] Klement, Laura; Bach, Martin; Geupel, Markus; Breuer, Lutz (2021): Calculation of a food consumption nitrogen footprint for Germany. In Environ. Res. Lett. 16 (7), p. 75005. DOI: 10.1088/1748-9326/ac09ad.

Appendix B. Flow chart

Flow charts and model results can be found on the TU Cloud under the following link :

https://tubcloud.tu-berlin.de/s/4EP3byYaQjtMeiL

In this folder, 10 figures regarding material and nitrogen flow charts can be found:

- Framework for N flow analysis of baseline scenario 2016
- Framework for material flow analysis of baseline scenario 2016
- Framework for N flow analysis of baseline scenario 2020
- Framework for material flow analysis of baseline scenario 2020
- Framework for N flow analysis of theoretical scenario
- Framework for material flow analysis of theoretical scenario
- Framework for N flow analysis of technical scenario
- Framework for material flow analysis of technical scenario
- Framework for N flow analysis of future sustainable scenario
- Framework for material flow analysis of future sustainable scenario

Appendix C. Results

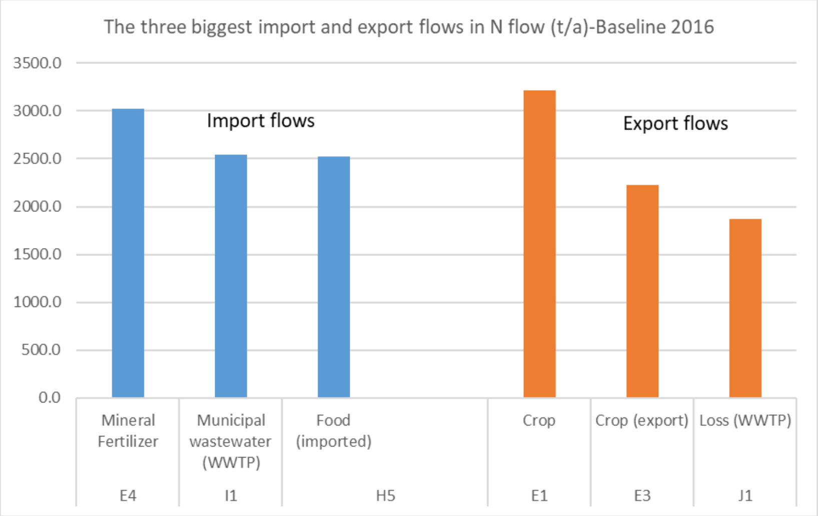

Figure (appendix) C-1 The three biggest import and export in N flow-Baseline scenario 2016

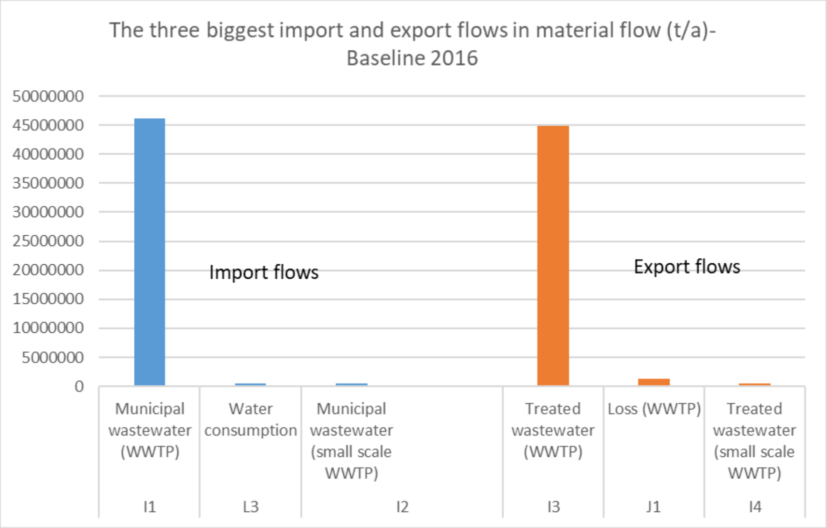

Figure (appendix) C-2 The three biggest import and export in material flow-Baseline scenario 2016

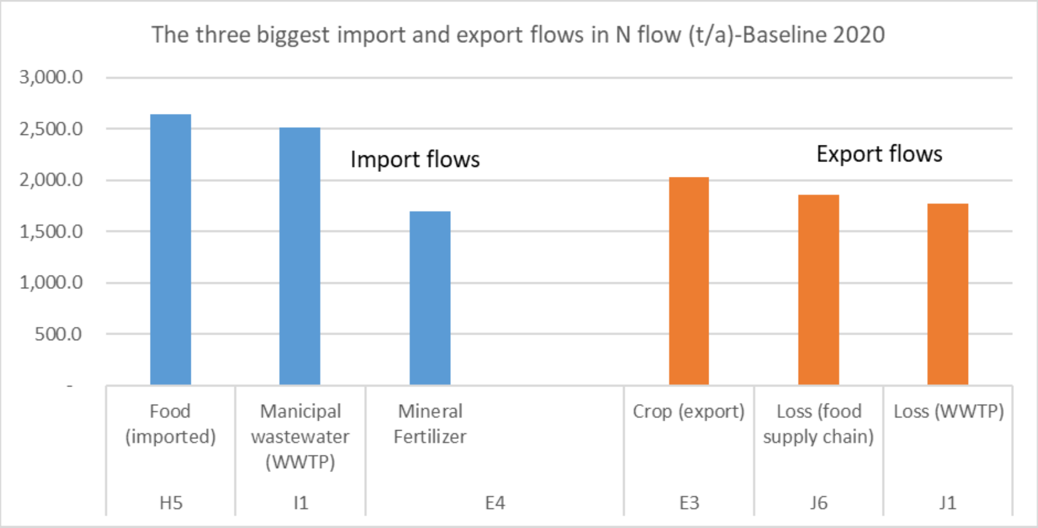

Figure (appendix) C-3 The three biggest import and export in N flow-Baseline scenario 2020

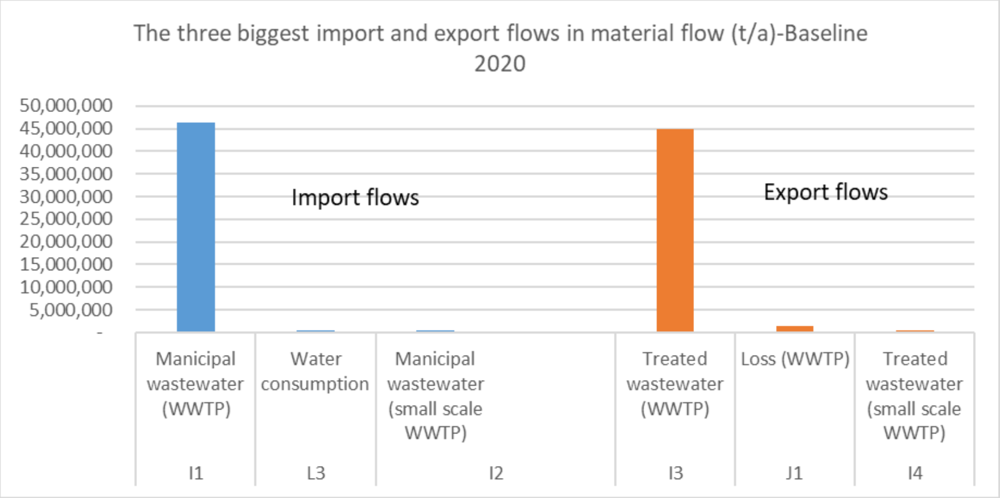

Figure (appendix) C-4 The three biggest import and export in material flow-Baseline scenario 2016

Table (appendix) C-1 Summary of the material flow and nitrogen flow result of the termophilic cmposting plant in 2022

	Result of thermophilic composting plant	Material flow		Nitrogen flow	
Flow	Flow name	Mass Flow (t/a)	± t/a	Mass Flow (t/a)	± t/a
F1	Urine	800.0		6.10	
F10	Unsieved humus fertilizers	106.1	5.3	0.54	0.03
F11	Urine for pilot plant	133.0		1.01	
F12	Urine for sewage treatment plant	667.0		5.09	
F13	Activated carbon	0.7		-	
F14	Treated urine	133.0		1.01	
F15	Liquid fertilizer	25.9		1.01	
F16	Disposal via wastewater	107.1		-	
F17	Activated carbon with drug residues and other trace substances	0.7		-	
F18	Solids (feces and impurities)	86.5		0.74	0.00
F19	Straw	1.6		0.01	
F2	Feces	67.0	0.0	0.71	0.00
F20	Toilet paper	16.7	0.0	0.02	0.00
F21	Green waste	38.3		0.10	0.00
F22	Shredded green waste	14.1		0.04	
F27	Clay minerals	2.9		-	
F28	Gas emission, wastewater treatment plant effluent, sewage sludge	667.0		5.09	
F29	Mass loss	8.7		0.27	0.00
F3	Hygenized solid materials	77.9		0.47	
F30	Woody oversize	23.0		0.06	0.00
F31	Shredded green waste	1.2		0.00	
F32	Carbon from plant	0.1		0.00	
F33	Water	50.1		-	
F4	Meadow, leaves and grass cuts	1.8		0.00	
F5	Oversize grain humus fertilizer	21.4	1.1	0.06	0.00
F6	Humus fertilizer	16.4	0.8	0.09	0.00
F7	Humus fertilizer	42.3	2.1	0.22	0.01
F8	Sieve residue	0.2		0.00	
F9	Mass loss	78.7	5.5	0.12	0.03

Table (appendix) C-2 The calculated results of 5 scenarios (material flow)

Material flow result		Baseline 2016		2020		Theoretical Scenario		Technical Scenrio		Future Scenrio	
		Mass Flow (t/a)	± t/a	Mass Flow (t/a)	± t/a	Mass Flow (t/a)	± t/a	Mass Flow (t/a)	± t/a	Mass Flow (t/a)	± t/a
A1	Feces (WWTP)	8,661	5,522	9,186	5,857	9,186.3		9,186.3		9,645.6	
A2	Urine (WWTP)	87,736	639	93,059	678	93,058.7		93,058.7		97,711.6	
A3	Feces (collecting pit)	990	631	903	576	903.1		903.1		948.2	
A4	Urine (collecting pit)	10,030	73	9,148	67	9,148.1		9,148.1		9,605.5	
A5	Feces (small scale WWTP)	104	66	99	63	99.3		99.3		104.3	
A6	Urine (small scale WWTP)	1,052	8	1,006	7	1,006.3		1,006.3		1,056.6	
B1	Biowaste from Biobin (urban)	1,508	75	17,843	892	17,842.9	892.1	17,842.9	892.1	17,506.6	740.2
B2	Biowaste from Biobin (rural)	206	10	2,433	122	2,433.1	121.7	2,433.1	121.7		
B3	Green waste (park/garden)	22,284	1,114	24,302	1,215	18,468.4	923.4	23,728.0	1,186.4	24,914.4	1,245.7
B4	Biowaste from other sources	5299.89 (lost to residue waste)	3,501	12,950	3,765	12,950.1	3,765.1	12,950.1	3,765.1	12,852.6	595.6
B5	Other bio material for composting	769	38	3,373	169	3,373.0	168.7	3,373.0	168.7	3,373.0	168.7
C1	Sewage sludge (WWTP)	20,764	903	23,390	1,038	17,425.5	1,835.4	21,471.8	2,192.0	21,307.3	2,217.0
C2	Sludge as fertilizer for agriculture	3,072	154	2,963	148	2,210.0	231.5	2,720.2	276.4	614.7	64.0
C3	Sewage sludge from small WWTP	184	8	207	9	154.2	16.2	190.0	19.4	188.6	19.6
C4	Sewage sludge output (thermal treatment/ export)	17,951	898	20,734	1,037	15,469.7	1,620.2	19,041.6	1,934.9	20,981.1	2,172.7
C5	Imported sewage sludge	75	4	100	5	100.0	5.0	100.0	5.0	100.0	5.0
D1	Fertilizer for agriculture and forestry (OFMSW)	6,090	914	8,584	1,288	8,144.6	1,186.6	8,522.3	1,246.8	8,249.3	1,207.3
D2	Fertilizer for Landscaping and maintenance/ recultivation (OFMSW)	4,285	643	4,848	727	4,611.0	671.8	4,824.8	705.9	4,670.2	683.5
D3	Fertilizer for private household (OFMSW)	3,523	528	4,268	640	4,050.8	590.1	4,238.6	620.1	4,102.8	600.4
E1	Crop	340,702	17,035	317,150	15,858	317,150.0	15,857.5	317,150.0	15,857.5	317,150.0	15,857.5
E2	Fodder (crop production)	87,531	66,696	78,243	65,403	76,948.6	65,634.4	78,257.7	66,334.4	74,852.7	67,837.5
E3	Crop (export)	236,050	69,355	221,027	67,875	222,321.1	68,098.5	221,012.1	68,773.4	203,488.3	72,036.0
E4	Mineral Fertilizer	10,074	1,511	5,645	847	5,645.1	846.8	5,645.1	846.8	5,645.1	846.8
E5	Metabolism demand from environment (crop)	1,211,093	968,874	1,124,312	899,450	1,124,312.4	899,449.9	1,124,312.4	899,449.9	1,124,312.4	899,449.9
F1	Fertilizer for intercrop	10,981	5,491	15,707	7,854	15,707.4	7,853.7	15,707.4	7,853.7	15,707.4	7,853.7
F2	Intercrop as green fertilizer	36,104	18,052	28,955	14,477	28,954.9	14,477.4	28,954.9	14,477.4	28,954.9	14,477.4
F3	Intercrop for forage production	6,656	3,328	20,864	10,432	20,864.2	10,432.1	20,864.2	10,432.1	20,864.2	10,432.1
F4	Metabolism demand from environment	48,382	38,705	63,972	51,178	63,972.3	51,177.8	63,972.3	51,177.8	63,972.3	51,177.8
G1	Digestate	190,119	28,518	199,890	29,984	199,890.1	29,983.5	199,890.1	29,983.5	199,890.1	29,983.5
G2	Manure (direct use)	193,046	28,957	136,984	20,548	136,984.3	20,547.7	136,984.3	20,547.7	124,749.6	18,712.4
G3	Manure (grazing)	21,764	6,529	19,752	5,926	19,752.1	5,925.6	19,752.1	5,925.6	19,752.1	5,925.6
G4	Farm products	65,996	19,799	64,987	19,496	64,986.6	19,496.0	64,986.6	19,496.0	58,939.4	17,681.8
G5	Farm products (export)	30,766	25,921	28,193	26,181	28,192.6	26,180.7	28,192.6	26,180.7	16,343.6	26,593.6
H1	Food intake	91,211	26,755	95,260	27,943	95,260.3	27,942.7	95,260.3	27,942.7	99,831.7	26,892.6
H2	Food intake (from regional crop production)	17,120	8,461	17,880	8,836	17,880.2	8,836.2	17,880.2	8,836.2	38,809.0	18,324.9
H3	Food intake (farm product)	35,230	16,731	36,794	17,474	36,794.0	17,473.8	36,794.0	17,473.8	42,595.8	19,863.9
H4	Drinking water (human)	98,202	49,101	102,570	51,285	102,570.3	51,285.1	102,570.3	51,285.1	107,698.8	53,849.4
H5	Food (imported)	52,350	23,176	54,674	24,205	54,674.2	24,204.7	54,674.2	24,204.7	27,127.9	13,198.1
H6	Food waste household	7,014	3,500	7,326	3,656	7,325.9	3,655.8	7,325.9	3,655.8	4,654.0	820.8
I1	Municipal wastewater (WWTP)	46,084,498	6,912,675	46,227,258	6,934,089	43,555,820.6	6,533,373.1	45,988,148.2	6,898,222.2	44,407,302.0	6,661,095.3
I2	Municipal wastewater (small scale WWTP)	447,779	67,167	407,416	61,112	381,113.5	57,167.0	381,113.5	57,167.0	400,169.2	60,025.4
I3	Treated wastewater (WWTP)	44,806,158	6,720,924	44,949,367	6,742,405	42,249,145.9	6,337,371.9	44,707,681.3	6,706,152.2	43,179,219.4	6,476,882.9
I4	Treated wastewater (small scale WWTP)	435,467	65,320	396,266	59,440	369,680.1	55,452.0	369,680.1	55,452.0	388,164.1	58,224.6
J1	Loss (WWTP)	1,364,993	9,641,365	1,366,797	9,671,693	1,372,335.7	9,102,046.5	1,369,414.3	9,620,704.3	1,322,715.5	9,290,866.9
J2	Loss (agriculture)	4,773	4,503	3,265	3,080	4,015.9	3,788.6	3,336.0	3,147.2	3,252.1	3,068.1
J3	Loss (farm)	258,347	273,503	220,101	237,374	212,898.9	234,734.1	210,611.0	237,370.7	186,687.1	218,322.4
J4	Loss (small scale WWTP)	13,284	93,691	12,049	85,251	11,279.2	79,642.9	11,243.4	79,642.9	11,816.5	83,625.1
J5	Loss (biowaste treatment)	10,868	1,666	30,251	2,216	28,811.2	1,673.1	30,135.6	1,794.8	29,133.3	1,739.7
J6	Loss (food supply chain)	6,474	3,232	6,762	3,376	6,762.3	3,375.6	6,762.3	3,375.6	4,046.9	2,022.5
J7	Loss (intercrop)	16,603	43,188	29,861	54,766	29,860.6	54,765.6	29,860.6	54,765.6	29,860.6	54,765.6
J8	Loss (human)	80,841	56,197	84,429	58,703	84,428.9	58,403.4	84,428.9	58,403.4	88,458.7	60,191.1
K1	Straw	82,711	15,799	78,359	14,944	78,358.8	23,507.6	78,358.8	23,507.6	78,358.8	23,507.6
K2	Straw for bedding	7,780	2,328	7,593	2,272	7,593.4	2,278.0	7,593.4	2,278.0	7,593.4	2,278.0
K3	Straw for animal feeding	67,438	15,733	63,689	14,878	63,445.5	23,713.0	63,664.6	23,713.0	63,663.4	23,713.0
K4	Humus	7,493	2,242	7,077	2,118	7,076.5	2,123.0	7,076.5	2,123.0	7,076.5	2,123.0
L1	Fodder	219,980	109,990	214,958	107,479	212,557.5	106,278.7	214,958.3	107,479.2	196,806.6	98,403.3
L2	Imported fodder	58,354	44,464	52,162	43,602	51,299.1	43,756.2	52,171.8	44,222.9	37,426.3	33,918.8
L3	Water consumption	492,268	246,134	414,678	207,339	409,876.1	204,938.1	414,677.8	207,338.9	381,133.2	190,566.6
L4	Grazing forage	20,225	1,430	20,192	1,428	20,192.5	1,427.9	10,702.0	605.6	20,192.5	1,427.7
T1	Carbon from plants					16.73	0.00	1.65	0.00	1.73	
T10	Shredded green waste					2,150.95	0.00	211.66	0.00	222.23	
T11	Oversize grain humus fertilizer					3,183.00	159.15	320.93	16.05	332.30	16.62
T12	Clay minerals					441.14	0.00	43.41	0.00	45.58	
T13	Meadow, leaves and grass cuts					273.81	0.00	26.94	0.00	28.29	
T14	Straw					243.31		24.24		25.46	
T15	Urine					103,213.07		10,154.41		10,662.13	
T16	Solids (feces and impurities)					13,161.60		1,295.11		1,359.83	
T17	Active carbon					543.23	0.00	53.44	0.00	56.12	
T18	Toilet paper					2,547.16		250.52		263.00	
T19	Water					7,624.16	0.00	750.22	0.00	787.71	
T2	Active carbon with trace substances					543.23	0.00	53.44	0.00	56.12	
T20	Unsieved humus fertilizers					16,119.00	805.95	1,587.56	79.38	1,643.83	82.19
T21	Humus fertilizer					6,387.00		632.57		654.99	
T22	Shredded green waste					182.48		17.96		18.86	
T23	Green waste					5,833.58	0.00	574.04	0.00	602.73	
T24	Loss of mass					11,849.24	830.47	1,178.63	81.91	1,252.35	84.81
T25	Woody oversize					3,500.15	0.00	344.42	0.00	361.64	
T3	Liquid fertilizer					20,126.55	0.00	1,980.11	0.00	2,079.12	
T4	Disposal via wastewater					83,086.52	0.00	8,174.30	0.00	8,583.01	
T5	Humus fertilizer					2,433.00	121.65	245.78	12.29	254.49	12.72
T6	Sieve residue					28.90	0.00	2.84	0.00	2.99	
T7	Loss of mass					1,316.16	0.00	129.51	0.00	135.98	
T8	Treated Urine					103,213.07		10,154.41		10,662.13	
T9	Hygenized solid materials					11,845.44	0.00	1,165.60	0.00	1,223.85	

Table (appendix) C-3 The calculated results of 5 scenarios (N flow)

N flow result		Baseline 2016		2020		Theoretical Scenario		Technical Scenrio		Future Scenrio	
		Mass Flow (t/a)	± t/a	Mass Flow (t/a)	± t/a	Mass Flow (t/a)	± t/a	Mass Flow (t/a)	± t/a	Mass Flow (t/a)	± t/a
A1	Feces (WWTP)	104.6	52.3	111.0	55.5	111.0		111.0		116.5	
A2	Urine (WWTP)	639.4	523.1	678.2	554.9	678.2		678.2		712.1	
A3	Feces (collecting pit)	12.0	6.0	10.9	5.5	10.9		10.9		11.5	
A4	Urine (collecting pit)	73.1	59.8	66.7	54.6	66.7		66.7		70.0	
A5	Feces (small scale WWTP)	1.3	0.6	1.2	0.6	1.2		1.2		1.3	
A6	Urine (small scale WWTP)	7.7	6.3	7.3	6.0	7.3		7.3		7.7	
B1	Biowaste from Biobin (urban)	9.9	0.5	117.0	5.9	117.0	5.9	117.0	5.9	114.8	4.9
B2	Biowaste from Biobin (rural)	1.3	0.1	15.9	0.8	15.9	0.8	15.9	0.8		
B3	Green waste (park/garden)	148.2	7.4	161.6	8.1	122.8	6.2	157.8	7.9	165.7	8.3
B4	Other bio material for composting	44.8702736 (lost to residue waste)	16.8	74.4	18.5	74.4	18.5	74.4	18.5	85.5	4.0
B5	Other bio material for composting	5.2	0.3	22.6	1.1	22.6	1.1	22.6	1.1	22.6	1.1
C1	Sewage sludge (WWTP)	914.5	137.8	1,030.1	158.5	776.3	51.9	1,007.7	53.2	994.4	51.2
C2	Sludge as fertilizer for agriculture	135.3	23.3	130.5	22.4	97.5	18.3	121.0	22.3	27.1	5.2
C3	Sewage sludge from small WWTP	8.1	1.4	9.1	1.6	6.6	0.4	6.8	0.4	7.1	0.5
C4	Sewage sludge output (thermal treatment/ export)	790.6	135.9	913.1	157.0	689.8	50.0	897.8	52.6	978.7	50.4
C5	Imported sewage sludge	3.3	0.6	4.4	0.8	4.4	0.8	4.4	0.8	4.4	0.8
D1	Fertilizer for agriculture and forestry (OFMSW)	42.6	8.8	60.1	12.4	57.0	1.6	59.7	1.9	57.7	1.8
D2	Fertilizer for Landscaping and maintenance/ recultivation (OFMSW)	30.0	6.2	33.9	7.0	32.3	0.9	33.8	1.1	32.7	1.0
D3	Fertilizer for private household (OFMSW)	24.7	5.1	29.9	6.2	28.4	0.8	29.7	0.9	28.7	0.9
E1	Crop	3,214.3	160.7	2,935.7	146.8	2,935.7	146.8	2,935.7	146.8	2,935.7	146.8
E2	Fodder (crop production)	825.8	630.6	738.2	618.1	725.9	620.3	738.3	626.9	706.2	641.0
E3	Crop (export)	2,227.0	655.7	2,028.9	640.8	2,041.2	642.9	2,028.8	649.3	1,863.4	680.2
E4	Mineral Fertilizer	3,022.3	453.4	1,693.5	254.0	1,693.5	254.0	1,693.5	254.0	1,693.5	254.0
E5	Metabolism demand from environment (crop)	1,021.6	306.5	1,172.5	351.7	1,172.5	351.7	1,172.5	351.7	1,172.5	351.7
F1	Fertilizer for intercrop	49.4	24.7	70.7	35.3	70.7	35.3	70.7	35.3	70.7	35.3
F2	Intercrop as green fertilizer	126.4	63.2	101.3	50.7	101.3	50.7	101.3	50.7	101.3	50.7
F3	Intercrop for forage production	23.3	11.6	73.0	36.5	73.0	36.5	73.0	36.5	73.0	36.5
F4	Metabolism demand from environment	122.0	61.0	139.6	41.9	139.6	41.9	139.6	41.9	139.6	41.9
G1	Digestate	1,140.7	171.1	1,199.3	179.9	1,199.3	179.9	1,199.3	179.9	1,199.3	179.9
G2	Manure (direct use)	984.6	295.4	682.5	204.8	682.5	204.8	682.5	204.8	627.2	188.2
G3	Manure (grazing)	94.3	28.3	94.2	28.3	94.2	28.3	94.2	28.3	94.2	28.3
G4	Farm products	453.9	136.2	482.1	144.6	482.1	144.6	482.1	144.6	449.6	134.9
G5	Farm products (export)	211.6	178.7	229.1	188.5	229.0	188.5	229.1	188.5	156.7	192.5
H1	Food intake	1,092.5	54.6	1,148.8	57.4	1,148.8	57.4	1,148.8	57.4	1,206.2	60.3
H2	Food intake (from regional crop production)	161.5	80.2	168.7	83.8	168.6	83.7	168.7	83.8	366.1	173.8
H3	Food intake (farm product)	242.3	115.7	253.0	120.8	253.1	120.9	253.0	120.8	292.9	137.4
H4	Drinking water (human)	-		-		-		-		-	
H5	Food (imported)	2,527.7	903.8	2,647.9	944.0	2,647.8	944.0	2,647.9	944.0	1,651.9	579.3
H6	Food waste household	56.1	16.8	58.6	17.6	58.6	17.6	58.6	17.6	29.4	5.4
I1	Municipal wastewater (WWTP)	2,542.9	178.0	2,516.1	176.1	2,504.2	167.3	2,461.5	171.8	2,379.0	165.3
I2	Municipal wastewater (small scale WWTP)	23.9	1.7	21.3	1.5	21.4	1.4	21.9	1.4	22.8	1.5
I3	Treated wastewater (WWTP)	582.5	87.4	584.3	87.7	425.7	28.4	552.6	29.2	545.3	28.1
I4	Treated wastewater (small scale WWTP)	21.8	3.3	19.8	3.0	14.2	0.9	14.5	1.0	15.2	1.0
J1	Loss (WWTP)	1,875.1	581.7	1,768.3	614.6	1,302.2	87.0	1,690.3	89.3	1,667.9	85.9
J2	Loss (agriculture)	2,386.5	1,193.3	1,632.6	816.3	2,008.0	1,004.0	1,668.0	834.0	1,626.1	813.0
J3	Loss (farm)	30.3	1,354.9	352.6	1,403.3	352.6	1,403.3	352.6	1,403.3	256.9	1,310.5
J4	Loss (small scale WWTP)	2.9	7.4	0.9	7.1	0.6	0.0	0.6	0.0	0.6	0.0
J5	Loss (biowaste treatment)	67.3	14.1	193.3	18.6	184.0	5.3	192.5	6.1	186.4	5.9
J6	Loss (food supply chain)	1,782.9	891.4	1,862.2	931.1	1,862.2	931.1	1,862.2	931.1	1,075.4	537.7
J7	Loss (intercrop)	21.8	92.0	35.9	83.1	35.9	83.1	35.9	83.1	35.9	83.1
J8	Loss (human)	254.5	532.0	273.5	563.3	273.5	57.4	273.5	57.4	287.2	60.3
K1	Straw	456.1	14.7	413.3	13.2	414.0	13.2	413.4	13.2	413.4	13.2
K2	Straw for bedding	38.9	1.9	38.0	1.9	38.0	1.9	38.0	1.9	38.0	1.9
K3	Straw for animal feeding	379.7	14.6	339.9	13.2	339.4	13.2	339.9	13.2	339.9	13.2
K4	Humus	37.5	1.9	35.4	1.8	35.4	1.8	35.4	1.8	35.4	1.8
L1	Fodder	2,607.1	1,303.6	2,736.5	1,368.2	2,736.5	1,368.2	2,736.5	1,368.2	2,552.9	1,276.5
L2	Imported fodder	1,378.3	1,448.0	1,585.4	1,500.5	1,598.1	1,501.3	1,585.3	1,504.1	1,433.8	1,427.2
L3	Water consumption	-		-		-		-		-	
L4	Grazing forage	107.2	5.4	107.0	5.4	107.0	5.4	107.0	5.4	107.02	5.35
T1	Carbon from plants					0.03	0.00	0.00	0.00	0.00	
T10	Shredded green waste					14.30		1.41		1.48	
T11	Oversize grain humus fertilizer					16.53	0.83	1.67	0.08	1.73	0.09
T12	Clay minerals					-		-		-	
T13	Meadow, leaves and grass cuts					0.68	0.00	0.07		0.07	
T14	Straw					1.28		0.13		0.13	
T15	Urine					752.18		74.00		77.70	
T16	Solids (feces and impurities)					127.94	0.00	12.59	0.00	13.21	
T17	Active carbon					-		-		-	
T18	Toilet paper					2.37		0.23		0.24	
T19	Water					-		-		-	
T2	Active carbon with trace substances					-		-		-	
T20	Unsieved humus fertilizers					81.19	4.06	8.00	0.40	8.28	0.41
T21	Humus fertilizer					33.17		3.28		3.40	
T22	Shredded green waste					1.21		0.12		0.13	
T23	Green waste					38.79	0.00	3.82	0.00	4.01	
T24	Loss of mass					78.14	4.19	7.75	0.41	8.21	0.43
T25	Woody oversize					23.28		2.29		2.40	
T3	Liquid fertilizer					752.18		74.00		77.70	
T4	Disposal via wastewater					-		-		-	
T5	Humus fertilizer					12.63	0.63	1.28	0.06	1.32	0.07
T6	Sieve residue					0.18	0.00	0.02	0.00	0.02	
T7	Loss of mass					12.79	0.00	1.26	0.00	1.32	0.00
T8	Treated Urine					752.18		74.00		77.70	
T9	Hygenized solid materials					115.15	0.00	11.33	0.00	11.89	0.00