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Decay as a mode of biogas production: Digestive assemblages and value creation through microbial work

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Abstract
Decay is usually understood as a process in which things break down, rot, and ruin. At first glance, the idea of decay is rather alien to our understanding of productive activity. In the context of the circular economy, however, the process of decomposition is harnessed as a tool of production through the anaerobic digestion of biowaste. In this process, waste turns into energy and nutritious fertilizer. This article studies decay as a mode of production in the context of the circular economy transition by focusing on more-than-human waste work carried out by microbes. The article is based on ethnographic fieldwork conducted in two Finnish biogas plants and interview material collected in Finland and Sweden. The article draws from the concepts of encounter value, marketization and digestive assemblages and studies how value is produced in three different phases of break down: biowaste, slurry, and digestate. It investigates the paradox of value creation and ruination, and aims to enrich the concept of production in the context of the circular economy through the introduction of decay as a value-producing process based on microbial work. Our analysis illustrates how the things produced in the process are not always desirable and how creating economic value for the end products of the biogas process is a volatile endeavor. Through our analysis, we argue that while the logic of the circular economy enables celebrating decay as a mode of capitalist production, the value produced through decay is still not necessarily mainly economic but, rather, symbolic.

Keywords
Biogas production, circular economy, decay, digestive assemblages, encounter value, marketization, microbial work, ruination

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Introduction

This article spotlights the social life of microbes – invisible waste workers that contribute to waste treatment practices in endless ways. Specifically, we focus on the work of microbes in the context of anaerobic digestion at biogas plants. Anaerobic digestion is a process in which various kinds of microbes break down organic waste in the absence of oxygen. In biogas plants, this process of decay produces two different tradeable products: biogas and fertilizers. Through transforming organic waste into these products, biogas plants adopt the circular economy (CE) as their business model. The CE is a model that is highly celebrated globally (Winans et al., 2017). The idea of the CE is that in the age of consumerism and abundance, societies are able to reuse and transform material in order to reduce waste. In the process, new values and products are created, thus demonstrating the saying that "your trash is someone else's treasure" (see also Reno, 2009) (Image 1).

Decay has often been understood as a process in which things rot, ruin, and lose their value. Although the process as such is neither productive nor non-productive, it is widely used for profitable aims. Through the example of anaerobic digestion in the biogas industry, we demonstrate how decay can be seen as a productive process that may create economic, symbolic, and environmental value.

Decay has been previously studied, among other ways, through focusing on our entanglements with waste – as our way of life produces enormous masses of waste, we are constantly living in the ruins of capitalist production while, at the same time, the practices of wasting transform the environment into ruins (Pyyhtinen et al., 2023). Furthermore, ideas such as "broken world thinking" have aimed to direct attention away from processes of growth and progress toward decay and breakdown (Jackson, 2013). As things and infrastructure are in a constant process of decay, they also require constant, mostly invisible maintenance and repair practices – work that creates the "normal" order of things and that we often take for granted in our everyday lives (Graham and Thrift, 2007). Decay, alongside repair and maintenance, can be understood as a specific phase of infrastructure's lifespan – one that is closely tied to issues of social (in)justice and the uneven distribution of resources (Ramakrishnan et al., 2021).

In this article, however, our focus is not on the practices of repair and maintenance that aim to create non-decay; instead, we illustrate how the process of break down itself can be made productive through different practices. Although these practices may, and often do, still entail maintenance and repair, rather than aiming to solve the problems caused by decay, this repair and maintenance aims to embrace decay. However, in the same manner as, for example, water infrastructure (see Hurst et al., 2022), waste infrastructure operates through the doings of both human and more-than-human actors. Thus, we investigate decay through a more-than-human lens.

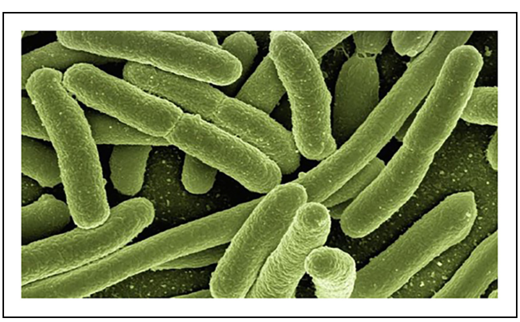

Image 1. Anaerobic microbes (Source: Pixabay).

In more detail, we examine the microbial process in which biowaste breaks down. In this process of decay, microbes feed on biowaste, and this transforms the waste into matter that can be utilized by humans, which enables capitalist production. While there exists a large body of research that has criticized the CE from multiple perspectives (see, e.g., Corvellec et al., 2022; Korhonen et al., 2018), few studies so far have critically examined the logic of production in the context of the CE or the potential of decay as a capitalist mode of production.

By focusing on decay as a productive process, the article expands the social scientific discussion on value production (Greeson et al., 2020; Helgesson and Muniesa, 2013; Muniesa, 2012), especially the understanding of the role of more-than-human actors in production and value creation processes (Coulter, 2016; Porcher, 2014). Our analysis also contributes to the current literature on the CE (Holmberg and Ideland, 2021; Lehtokunnas and Pyyhtinen, 2023; Hobson et al., 2021; Schulz et al., 2019) by reassessing and complicating the ideas of value production in the context of the CE. We argue that examining decay is crucial for critically assessing the anthropocentric logic of the CE. The present article thus departs from the apparent paradox of value creation and ruination and aims to enrich the concept of production in the context of the CE through introducing decay as a value-producing process based on microbial work.

When examining microbial work, we draw on the concept of "encounter value" (Barua, 2016; Haraway, 2008). Encounter value refers to a relational understanding of value production in which non-humans are seen as laboring subjects. According to this understanding, value is produced in encounters between different species, such as – in our case – humans and microbes. However, although decay can produce value, the circularity of biowaste is difficult to uphold due to legal, social, and technical obstacles. In our example of biogas production, the flow of incoming biowaste needs to be stable in order to secure the supply and demand balance, and there is constant "make up work" being performed in order to juggle this balance (Holmberg and Ideland, 2021). This means that the CE and production in this context need close maintenance to run effectively. Thus, while microbes work to break down the waste, infrastructure, management, policy, markets, and maintenance practices are also needed. Together with microbial work, these elements shape the marketization (Çalışkan and Callon, 2010; Pütz, 2021) of biowaste and fertilizers.

We explore the different more-than-human elements that participate in the process of production and contribute to turning biowaste into valuable goods, through the lens of "digestive assemblages" (Holmberg, 2019). This choice follows the argument above about the more-than-human approach to production and how decay provides new ways of imagining agency and rationality in the CE. Assemblage thinking attends to relationality, effects, and processes, which is productive if one wants to open up new critical yet constructive ways of doing social science (McFarlane and Andersson, 2011). In our specific case, microbes are at the very heart of analysis because they eat their way through masses of biowaste and release gas. Thus, the term "digestive" is a fitting one to pinpoint microbial action. Digestive assemblage thus refers to the assembly of actors and devices that run through the biogas chambers, enabling the value producing decay process.

Our data consist of fieldwork conducted in Finnish biogas plants and expert interviews with people working in the biogas sector in Finland and Sweden. In our analysis, we problematize the idea of a perfect CE by showing how microbes are not able to work with all the different material that arrives at the plants with biowaste, and how these materials thus decay in uncontrollable and undesirable ways. By shifting attention to production as a more-than-human process we illustrate how the human-centered idea of efficient production in the context of the CE may sometimes clash with the reality of microbial work. Our examination reveals how decay as a mode of production does not simply mean producing things that humans desire; the work of microbes also produces different kinds of problematic – unwanted – material. Moreover, we show that, on some occasions, it is not clear whether the value produced by microbes is economic but, rather, symbolic.

In the following, we review the theoretical framework that guides this article, paying close attention to the significance of biogas production and microbial work for the operation of the CE. We also develop the concepts of encounter value, digestive assemblages, and marketization in more detail. After this theoretical review, the ethnographic and interview data are presented. The following analysis section is organized into three different material phases of decay: biowaste, slurry, and digestate. Finally, we conclude by discussing our results and focus on the specifics of value production through microbial work and the potential of our case to problematize the human-centered idea of production in the context of the CE.

Decay as a mode of production

The circular economy and the microbial work of decay

In the EU, CE is currently seen as one of the main components of the transition toward "sustainable economic growth" (EU Commission, n.d.). Developing the operational environment of biogas plants is a central part of Finnish and Swedish national efforts for transitioning to a CE (see, e.g., Regeringskansliet, 2020; SOU 2019:63, 2019; Åkerman et al., 2020), especially through increasing the production of renewable energy and the circulation of nutrients through biogas production. The CE is opposed to the linear economic model of take–make–use–dispose, in which materials are exploited and then disposed of. Instead, the CE aims to "close the loops" by making materials circulate through reducing, reusing, and recycling (Ghisellini et al., 2016). The most optimistic promoters even highlight complete elimination of waste through the CE (Ellen McArthur Foundation, n.d.). However, CE as a model and ideology has also been critiqued from multiple different perspectives (see, e.g., Corvellec et al., 2022). Numerous scholars have, for example, pointed out that the slogan of waste to treasure is not as simple as it sounds but requires hands-on work, sensory practices, infrastructures, policies, and technology (Gille, 2010: 1054; Holmberg and Ideland, 2021; Lepawsky and McNabb, 2010; Lehtonen and Pyyhtinen, 2020). Along the way, the valuable gets turned into new trash that, in turn, gains new value in open-ended systems. Moreover, in practice, circular economies are packed with conflicts of goals. In biogas production, the ecological goal of recycling waste is at times not profitable, and infrastructures for biogas production demand a steady flow of new and more waste (Holmberg and Ideland, 2021). Moreover, biogas production is a CE solution that is largely based on technological solutionism and that "does not politically disrupt existing systems of environmental governance" (Koh, 2025: 1).

As stated previously, we problematize the idea of production in the context of the CE by focusing on decay as a productive, but also unruly, process of microbial work at biogas plants. According to dictionary definitions, the noun "decay" signifies rot and waste, and even death itself. It might be smelly, hazardous, or polluting. However, decay also refers to various things that get broken down and gradually move toward worthlessness. Typically, from a human perspective, the decomposition of biowaste in biogas facilities is framed as a passive or negative unilateral process of decay. Questioning this image, Ghassan Hage (2021) delves into the multiple meanings of decay, in particular its mortal figuration. For Hage, decay is, foremost, a liminal space as it signifies the not-yet-dead. Decay is the process of becoming dead or returning back to life. He thus puts the model to work in order to analyze social change. In a similar fashion, we investigate the process of biogas production through the lens of decay.

Biowaste cannot decay without microbes, which are particularly interesting multi-species workers. At biogas plants, microbes digest biowaste that is then converted into new products that ideally enter new economic cycles. However, regardless of their significance to the CE, microbes are not "big like us," and thus they have for a long time passed under the radar of scholars in the humanities and social sciences (Hird, 2009). Bacteria have moved from being viewed solely as disease-generating enemies that need to be combatted to create and keep a healthy population, to being positioned as friendly allies that help human – and animal – bodies function (see e.g., Gröndal, 2018). Microbe/human ecosystems have even been elevated to a role model for how humans should be involved in ecological relations (Paxson and Helmreich, 2014). This shift in our way of relating to microbes has been conceptualized as "microbiopolitics" (Paxson, 2008), implying a kind of microbial workforce. The concept refers to the ways in which humans live with microbes and how human encounters with microbes are governed through different practices. The work that microbes perform may be viewed in terms of the domestication times/spaces of waste infrastructures. As specific kinds of waste infrastructures, biogas plants can also be seen as "more-than-human contact zones" (Haraway, 2008; Isaacs and Otruba, 2019), where humans and microbes encounter in particular ways. In the following section, we spell out how these encounters are crucial for value production in the context of the CE.

Digestive assemblages, encounter value and the marketization of biowaste and fertilizers

Although the work of microbes is crucial for the decay process, microbes alone cannot turn biowaste into valuable products at biogas plants. As mentioned above, to examine the decay process as a mode of production, we draw from the concept of digestive assemblage. Digestive assemblages are constituted by multiple, heterogeneous kinds of actors – waste infrastructure, plant workers, legislation, biowaste, and so on – that participate in the process in which waste decays. Assemblages often imply processes rather than a particular state as well as a decentering of human actors and human intentionality (Bennett, 2010). As we zoom in on microbes and decay activities, we follow the waste flows into the biogas plants and the ways in which these tiny actors assemble with others along the route. Biowaste (over)flows the world and mobilizes relations and microbes are indispensable to these assemblages of "waste-worlds" (Hird, 2016). The notion of digestive assemblage thus refers to the complex metabolic relations in which the excess produced by economic activities get digested, simultaneously creating new products and new kinds of excess.

To conceptualize microbial work along the digestive assemblage, we draw on the concept of encounter value (Barua, 2016). Simply put, encounter value refers to different kinds of values that are produced through and in the encounters between humans and animals. Building on Donna Haraway's (2008) concepts of encounter value and lively commodities, Maan Barua states that "encounter value can be thought of as that process of value generation where bodies, ethologies and liveliness of an animal makes a difference to, and is constitutive of, those very relations that render or mobilize it as a commodity" (Barua, 2016: 728).

So far, the concept of encounter value has mainly been used to study encounters between humans and mammals. These studies have analyzed the impacts of the liveliness of animals on the process of commodification (Barua, 2016; Pütz, 2021), among other things. For example, ecotourism and biodiversity conservation in India have been studied as settings in which humans can encounter "charismatic" (Lorimer, 2007) animals, such as lions and elephants (Barua, 2016). These encounters between nonhuman animals and humans create capital for those who harness the lives of such animals. Encounter value can also differ by context. In his study on the marketization of the American Mustang, Robert Pütz (2021) shows how encounter value is constituted through the situated encounters between individual humans and horses. In these encounters, Pütz highlights, affection and corporeal communication between the human and the horse are central.

Microbes are not charismatic in the same way lions or elephants are, and human–microbe relations are not always affective. However, in the context of biogas production, creating encounter value with microbes still requires being attuned to them and understanding what kind of effects different actions and waste batches may have on them. Thus, the production of value depends on the careful orchestration of encounters between humans and microbes. By focusing on encounter value production in the context of microbial work, we highlight how microbes are not simply a resource that humans can utilize to produce capitalist value; they can also be perceived as social actors that have the capacity to affect social, environmental, and economic relations. In our analysis, we utilize the concept of encounter value to examine how value production happens in different human–microbe encounters within the digestive assemblage.

The digestive assemblage is also connected to multiple different relations far beyond the biogas plants. This becomes especially apparent when we consider the fact that microbes do not only conduct the labor of breaking down the waste but are also central from the viewpoint of the marketization (Çalışkan and Callon, 2010) of the end products of the biogas production process. Following Koray Çalışkan and Michel Callon (2010), by marketization, we refer to the active practices of creating markets for things. Marketization involves sociotechnical assemblages that consist of the multiple human and more-than-human elements, such as rules, technologies, knowledge, and embodied competences, that are crucial to the formation of markets. As the environmental and economic value of biogas and fertilizers depends on the microbial decay processes, microbes participate in the marketization of these products. However, as we show in our analysis, the possibilities for the marketization of these products are also shaped by multiple other actors (see also Lehtokunnas and Pyyhtinen, 2023), which often complicates the process of creating economic value. Moreover, as our analyses illustrate, microbial work can also generate forms of production that hinder the process of marketization and even completely compromise human-centered understandings of value and economic production.

Data and methods

Our data consist of ethnographic observations conducted in two Finnish biogas plants during 2021 and interviews with Finnish and Swedish biogas experts conducted between 2019 and 2021. The ethnographic fieldwork was conducted by the first author and lasted three weeks in total. During the fieldwork, the first author spent approximately five hours per day at the plants, talked with the plant workers, and helped out with some simple work tasks. Based on ethnographic observation and interviews, she wrote short jottings daily in the field and later expanded them into detailed field diary entries after each field day (79 pages in total) (Emerson et al., 1995). In addition, both authors have conducted expert interviews related to biogas production in Finnish and Swedish contexts. The interview data consist of 20 semi-structured interviews with Finnish and Swedish biogas experts.[1] These experts worked as managers at the biogas plants that we studied but also had key positions in other parts of the waste chain.

The data was analyzed through directed content analysis (Assarroudi et al., 2018). This means that the theoretical concepts of encounter value, digestive assemblages and marketization guided the analysis of the fieldwork notes and interview transcripts from the beginning. The analysis of the data started from systematic reading. During this phase, we were sensitive to instances that related to the work of microbes in the biogas production process. After this, we decided to divide the analysis section based on the different phases of the biogas production process, since the work of microbes was visible in different ways in these different phases. Finally, we wrote the analysis based on our findings related to the work of microbes.

It is crucial to note that although the data collection was conducted in two different countries, the legislation and problems of biogas production in these countries are rather similar, partly because both countries are EU Member States. In practice, for example, this means that sewage sludge and biowaste cannot be mixed in biogas plants, and this sets certain conditions for the production process. There are, however, also some differences between the two countries: in Sweden,

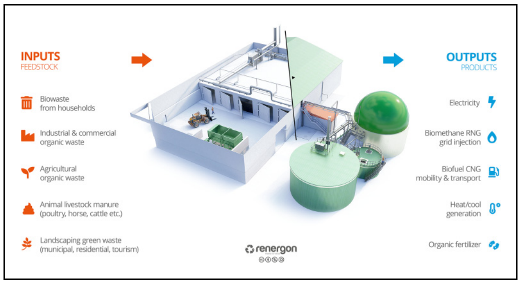

Image 2. The biogas production process. (Source: Wiki commons, retrieved 23 August 2024. Creator: Thzorro77. Created under the license CC BY-SA 4.0: https://creativecommons.org/licenses/by-sa/4.0/deed.en. Link to the content: https://commons.wikimedia.org/wiki/File:Biogas_Plant_Massflow.png).

households often pack their biowaste in paper bags, while Finnish households often use biodegradable plastic bags. However, regardless of differences in the production process, the work of microbes that is in the focus of this paper is still similar in both national contexts.

Analysis

Although biogas plants take different shapes and forms and are organized in different ways – both architecturally and according to different business models – the plants we studied through ethnographic observation and interviews still follow a similar model. Some of them, however, were larger in their capacity to treat waste than others, and some were privately owned while some were public enterprises. Yet, what was common was that they provided biowaste treatment services both for municipalities and private companies. In what follows, based on the ethnographic fieldwork conducted by the first author and the interviews carried out by both authors, we dive into the details of the work that goes on in the facilities and "follow the trash" (Holmberg and Ideland, 2021) as it flows and moves through different modes: from unsorted biowaste, to slurry, to digestate and gas (Image 2).

Biowaste

In this section, we analyze the orchestration of encounters between humans, different materials, and microbes in the first stage of decay at biogas plants – that is, the pretreatment process. At this stage, the pretreatment machinery in the plants crushes the biowaste and removes contaminants, such as packaging and metal, from it. The working of the pretreatment machinery is crucial for fostering the right kind of decay. This is because the material that arrives at the plants and that is treated under the title "biowaste" contains different materials that have very different liveliness and durability (see also Hawkins, 2023). It is rather fluid – in one of the plants, according to a waste trader interviewed, about a third consists of oil from grease separators. However, too much oil may disturb the microbes and hinder their work:

> Grease separators are interesting, they are taken from food production, in industries and commercial kitchens and things like that- /…/And fat is good to rot, it will disappear, we rot it all away, but you can't push too much because then it will, the bacteria don't really like that. /…/ Then they get fat and then they don't want to do anything. (Interview, April 2019)

This example illustrates a conflict of goals: on the one hand, a high level of fat content is pure and thus good for biogas production, but on the other hand, it is too massive for the microbes and risks

Image 3. Analyzing plastic (Source: Tora Holmberg).

being too one-sided as feed. The microbial workers need feed of the right kind and pace – as will be shown later.

In addition to the fact that the composition of the feed varies, biowaste is often packed in different kinds of wrapping: households usually pack their biowaste in biodegradable biowaste bags (and sometimes even in regular plastic bags), while the waste that comes from supermarkets and food industry businesses is packed in its original packaging. Moreover, sand often ends up among biowaste when biowaste bags are stored on the floor of biowaste reception halls at the plants. Microbes can work with the organic matter that biowaste contains (food scraps, peel, bones), but they cannot break down plastic, sand, and metal.

Machinery that removes packaging and other contaminants from biowaste is thus crucial for the plants. While the first author was shoveling dirt from the floor of the pretreatment hall together with the maintenance workers at one of the plants, they told her that the facility has very efficient plastic separation machinery that they have actively developed and enhanced over time. The plant machinery is constantly tinkered with when one gains knowledge and experience on the operation of the plant and the work of microbes. This illustrates how the digestion of biowaste at biogas plants cannot occur solely through the work of microbes; repair and maintenance practices are also crucial to the decay process. However, in addition that encounter value production requires repair and maintenance practices, the overflowing material that cannot be digested by microbes must be processed through alternative means, such as by transferring it to waste incineration plants. Thus, while plant workers and their repair practices are important parts of the digestive assemblage, the wider waste infrastructure is also crucial (Image 3).

It is, however, quite common for the pretreatment machinery (especially the plastic separation one) of biogas plants to not work very well, and because of this, microplastics may end up in biogas reactors (Öling-Wärnå et al., 2023), resulting in the production of biogas decreasing due to there being less space for biowaste within the reactors. While it may seem obvious that removing contaminants—such as plastic packaging—from biowaste at the source would solve most of the problems, doing so would require significant additional effort from supermarket employees and other business staff. This added workload could lead to economic inefficiencies in their operations. These problems illustrate that while the digestive assemblage is connected to wider waste infrastructures, such as waste incineration plants, it also relies on the waste sorting practices of households and businesses before waste enters the biogas plants. Plastics among biowaste slurry thus show that practices that are considered "efficient" in one context can create indigestion and inefficiency elsewhere in the assemblage.

However, it is crucial to note that despite the problems related to plastics, most of the material arriving at the plants is still suitable from the perspective of microbial work. The microbes start their work of breaking down waste before the waste arrives at the plants. Because of this, the biowaste that is loaded into the biowaste reception and pretreatment hall is smelly and slimy, and the floors of biowaste pretreatment facilities are full of fluid that drains out from the biowaste bags. This goo needs to be constantly cleaned and washed from the floors – microbes are messy workers, and encounter value production requires human labor to clean up. Moreover, microbes not only produce the desired methane, but also other, dangerous, gases, namely, hydrogen sulfide. The plants need to monitor the amount of this gas in their facilities, especially in the biowaste pretreatment hall. When the first author was conducting fieldwork, one of the maintenance workers warned her about hydrogen sulfide while they were cleaning the floor of the pretreatment hall together:

> The maintenance worker asked me if I knew the smell of hydrogen sulfide. I answered that I was not completely sure, and then the maintenance worker told me that it smells like rotten eggs. He told me that I should be cautious if I detect an odor like that. (Field diary entry, May 2021)

Although some waste batches, such as eggs, produce more hydrogen sulfide than others, biogas plants need to treat (almost) all kinds of biowaste, since the internal competition for incoming biowaste is so intense. Some waste batches may also cause other kinds of problems in the process, such as foaming. The problems caused by potentially unsuitable or otherwise problematic waste batches have consequences also from the viewpoint of encounter value production with microbes. Compared to many other forms of production in which non-human bodies such as cows or dogs (Haraway, 2008) are involved, decay as a form of production is different. While the diet of many domesticated animals that create added value is strictly controlled to produce desirable outcomes from the viewpoint of production (see, e.g., Driessen and Heutinck, 2015), the diet of microbes cannot be closely controlled. These issues also illustrate how biowaste is not homogenous mass but is "vibrant matter" (Bennett, 2010) that may create different kinds of effects in the digestive assemblage. Thus, microbes and the process of decay at the plants do not often work according to anthropocentric logic of efficient production. Because of this, the plants need to deal with the problems this potentially causes by, for example, using monitoring technology for gases such as hydrogen sulfide. This is crucial from the viewpoint of orchestrating the encounters between humans and microbes and being attuned both to the reality of microbial work and the process of decay in a micro-bio-political play (Paxson, 2008).

Moreover, the need to include and treat (almost) all kinds of biowaste once again illustrates how digestive assemblages are connected to the wider networks of waste economy. All biowaste that people produce needs to be treated in one way or another, regardless of the potential flaws it creates in the decay process. While in the context of the CE, biowaste has been turned into a resource for biogas production that the plants compete over, still all biowaste is not necessarily optimal material from a business model perspective. Considering the digestive assemblage, the understandings and goals related to efficient production may sometimes clash both with the reality of microbial work and imperatives related to treating waste in the most ecological and efficient way. In the next section, we further illuminate the practices of balancing between the productionist logic of biogas production and the unruliness and uncontrollability of microbial work.

Slurry

After the pretreatment process, biowaste has been crushed, squeezed, and liquidized into slurry – a wet, mucky, brownish substance. Being runny, it is moved through pipes into specific containers, in which its' temperature is kept around 35–40 degrees Celsius. It is important to keep the temperature of the slurry suitable for the microbes to enable them to work as efficiently as possible. From the containers, the slurry is fed to the biogas reactors at a suitable pace. Inside the reactors, the microbes start their most important work – that is, the digestion of biowaste and gas production (Image 4).

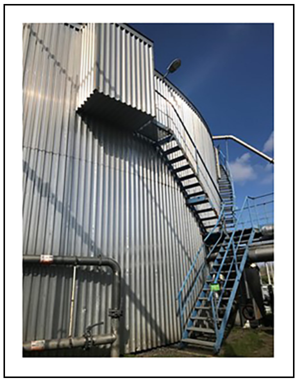

Image 4. Biogas reactor (Source: Tora Holmberg).

In the facilities where the fieldwork was conducted, the slurry was kept inside the reactors for 21 days, after which the microbes have broken it down and the remaining digestate will be removed. The orchestration of microbial work in the digestive assemblage is reliant on practices such as adjusting temperatures and the rhythms of keeping the slurry inside the reactors. Through this calculation and management, the biogas production process is made as efficient as possible. However, there are certain obstacles that disrupt the efficiency of gas production. In addition to gas, the microbes may produce other kinds of matter, such as foam:

> When we were sitting together and drinking coffee at the control room of the plant, one of the maintenance workers told me that he monitors the reactors from the computer screens next to us. According to him, the monitoring program shows how full the reactors are and if there is any foam inside the reactors. He said that in the worst case, the foam may get out from the reactor and spread around the plant area. (Field diary entry, May 2021)

The foam that the microbes produce inside the reactors may end up in the wrong places and cause problems in the process. For example, if the foam ends up in the pipes through which the gas is transported, it may break expensive machinery parts. To prevent the foam from ending up in the wrong places, the plant workers have to adjust the rhythm of feeding the slurry to the reactors. In addition, the level of foam inside the reactors is carefully monitored by using sensors, and depending on the plant infrastructure and technology, also by checking the level of foam through a window located on the side of the reactor. If the plant workers notice that there is too much foam inside the reactor, they can, for example, slow down the feeding. However, in addition to potentially causing foaming, the rhythms of feeding and the composition of the slurry affect the microbes in many other ways. One of our informants – a CEO – stated that the feeding of microbes is a delicate process, since the methane-producing ones are a precarious group:

> They don't like too high ammonium levels and they don't like too much variation, then there will be other groups that grow strong and then there can be foaming and other scenarios./…/ You have to think of it as a pet and sort of… feed it, or send in waste then, continuously then and don't put too much variety, because then other groups [of microbes] will grow strong. (Interview, November, 2018)

The interviewee stated the need to make the microbes "happy" and avoid making them overburdened. The eco-balance that is optimal for methane production should not be disturbed, since this could jeopardize the whole process. In order to prevent this, one can think of the microbes as "pets". However, from the viewpoint of encounter value production, unlike with many pets, here the value does not arise from encounters between individuals. Rather, the microbes are thought of as populations. It is crucial to cultivate the methane-producing microbes and avoid feeding other microbe groups. This illustrates the dynamics between care and avoidance in the practices of producing encounter value with microbes: not all actors in the digestive assemblage are as desirable as others. By steering the feeding process, the plant workers aim to ensure good, productive decay. This, again, shows how production along the digestive assemblage line occurs in the encounters between humans and microbes.

In addition to highlighting the importance of feeding correct microbe groups, the plant workers often stressed how important it is to always keep the "portion" and the composition (degree of dry vs. wet substance) of feed steady to keep the working conditions of the microbes as steady as possible and prevent problems. This means keeping both the size and rhythm of feeding steady. All the talk about pace, rhythm, steering and portion implies industrial production and control. However, there are so many factors that can interfere with this, and no matter how meticulously the process is monitored and the feeding is tinkered with, full control cannot be accomplished. In the worst case, if the slurry is fed too intensively into the process, the microbes may die:

> One of the maintenance workers told me that the whole biogas production process once stopped working completely in 2016. He showed me a figure that illustrated that the process fell down quite quickly, and the production of gas ended completely. The maintenance worker told me that one reason why the process 'died' was that biowaste was fed too intensively to the reactors. (Field diary entry, May 2021)

The fieldnote exemplifies how the work of microbes cannot be intensified too much, and this sets certain conditions for the process and its efficiency. In addition to scenarios in which the microbes die, aims to intensify the process may lead to, among other things, uncontrollable foaming. The unintentional production of foam, just as with the production on hydrogen sulfide mentioned in the previous section, is yet another example of how the process of decay is not always very productive from the perspective of value creation. While infrastructural solutions are needed to monitor the production of foam and hydrogen sulfide, skills for running the process correctly and attunement to the microbes are also needed.

Foaming and other undesirable outcomes of microbial work shape the digestive assemblage in many ways. While many materials, such as sand and plastics, that end up at biogas plants may be considered excess from the viewpoint of microbial work, microbes themselves also produce many kinds of excess while they work. Thus, like all forms of value creation (see Greeson et al., 2020), the microbial work of biogas production also ends up creating different kinds of excess, such as foam and dangerous gases. This kind of excess is an unavoidable part of the digestive assemblage, and managing it is part of being attuned to the microbes and thus creating productive decay. For example, one of the plant workers explained that if he hears a buzzing sound coming from a pipe, he knows that foam is being created in the decay process and that he must take action to remove it before it causes problems. Thus, the repair and maintenance practices of the plant workers do not aim to create non-decay but rather to embrace and understand the process of decay (see Jackson, 2013) to make it as productive as possible while recognizing the impossibility of perfect industrial control.

Decay as a form of production thus requires constant balancing between the logic of the business operations of biogas plants (calculation, monitoring, management) and the unruly reality of microbial work. Biogas plants as digestive assemblages are connected to discursive and cultural understandings that relate to the logic of the CE. However, as this section has shown, the digestive assemblage does not only entail digestion, but it also paradoxically creates indigestion of materials, such as foaming of the reactors and inefficiencies in waste treatment practices. The findings illustrate how the reality of microbial work often clashes with anthropocentric understandings of efficient production.

Digestate and gas

In this section, we analyze what happens after the work of microbes within biogas reactors has ended and highlight the effect that microbes have "on the generation of value and on marketization processes" (Pütz, 2021: 587) of biogas and fertilizers. By marketization (Çalışkan and Callon, 2010) we refer to the ways in which the liveliness of microbes and the specific qualities of biogas and fertilizers shape the organization of markets for biogas and fertilizers.

After the slurry has been broken down by the microbes, gas production within the reactors ends. At this stage, the biowaste slurry has been turned into mass that is called "digestate," which will be removed from the reactors. Here, it is important to take care that the microbes that may be hazardous for humans are removed so that the digestate can be safely used as fertilizer. To remove the unwanted microbes, the digestate is moved to sanitation tanks in which its temperature is increased to 70 degrees Celsius for a minimum. During the biogas production process, microbes are nursed to make their working conditions as good as possible, but after their work has ended, at least some of them (e.g., salmonella and e. coli) are destroyed. Although microbes are vital waste workers, consumer encounters with them must be controlled. This illustrates the dynamics of avoidance and care in encounter value production with microbes; hazardous bacteria are tolerated as waste workers, but when the products are moved to the markets and outside the more-than-human contact zone (Haraway, 2008; Isaacs and Otruba, 2019) of the biogas plant, their presence is no longer desirable.

After the digestate has been sanitized in a sanitation tank, it can be used as fertilizer, which is stored and distributed by the biogas plants. The fertilizers can be kept fluid, or they can be dried to allow different kinds of possibilities for use. The qualities of the dry and fluid fertilizers vary. They contain different amounts of nutrients, and different kinds are suitable for different plants and soil types.

The different wanted and unwanted materials that come to biogas plants with biowaste decay in different ways – the microbes will turn biowaste into digestate within 21 days or so, and this digestate is safe to be used as a fertilizer after sanitation. Microplastics, however, will not be broken down and thus they will be spread onto the fields. In this sense, the decay of biowaste and the different materials it contains continues even after the actual biogas production process at the plants has ended. Part of this decay is desirable, as plants and micro-organisms in the ground will benefit from the fertilizers. In this way, they are part of the digestive assemblage – after the fertilizer is moved out of the plant, the encounter value production continues in agriculture. However, decaying microplastics will clearly not create any added value in the fields. The end product of biogas production thus also contains material that is not valuable but rather is problematic waste; the circulation of nutrients comes together with the circulation of plastics. Thus, the indigestion that is created within this digestive assemblage is a problem both at the biogas plants and outside of them (Image 5).

In addition to the problems related to the indigestion of plastics, in many cases, selling the fertilizers does not produce a significant revenue stream for the plants (see also Lehtokunnas and Pyyhtinen, 2023). Farmers are often unwilling to pay for the fertilizers produced by biogas plants. Our informants reported many different potential reasons for this. Farmers may not, for example, be familiar to using the fertilizers produced by biogas plants, or they may not have suitable machinery for spreading it on their fields. Because of these issues, biogas facilities are often forced to give the fertilizers away for free and, in some cases, even pay the freight costs. When

Image 5. Different qualities of digestate (Source: Tora Holmberg).

the first author asked the CEO of one of the biogas plants whether he considered the production of biogas or fertilizers more profitable for them, it became clear that fertilizers are in fact quite problematic for the plants:

> The CEO said that fertilizers are a "necessary evil" for them, and they just try to somehow dispose of them. He said that at times it is hard to get rid of the fertilizers, and it is also difficult to obtain profit from them. (Field diary entry, June 2021)

The issues of distributing the fertilizers and creating monetary value from them illustrate how the digestive assemblage is shaped by not only the digestion or indigestion of waste itself but also the marketization of end products. The problems of creating markets for end products may create indigestion in the form of difficulties of moving forward the fertilizers. The marketization of the fertilizers does not depend only on the practices of biogas producers or the work of microbes but also on actors outside of the plant. Thus, the practices and preferences of farmers shape the possibilities of the marketization of the fertilizers. While the markets for fertilizers produced by biogas plants are underdeveloped in Finland and Sweden (Ekman Burgman and Wallsten, 2021; Winquist et al., 2019), the fertilizers are still considered valuable because of the environmental benefits of nutrient recycling (Humalisto et al., 2021).

Regardless of the difficulties of creating monetary value from fertilizers, our informants often strongly highlighted the importance of nutrient recycling. In fact, this was often a central part of the marketing practices of the biogas plants and thus also the marketization of both biogas and fertilizers. Moreover, practices such as giving the fertilizers away for free or paying the freight costs can also be seen as maintenance and repair that aims to embrace decay; the operations of the plants would be impossible if the end products were not moved forward in one way or another. Thus, this kind of maintenance is crucial for the metabolism of the CE, regardless of the economic inefficiencies it creates.

Image 6. Purification (Source: Tora Holmberg).

In addition to the fact that the fertilizers need to be moved forward in one way or another, even if doing so does not produce much revenue, the produced gas must, of course, also be distributed. Methane is a desirable component in the gas as it contains energy. The gas, however, also contains other, undesirable components, such as hydrogen sulfide, as we have already discussed earlier. Because of this, if the gas is used as traffic fuel, it must be purified. This means that the desirable methane must be separated from less desirable components (Image 6).

The gas can be used as traffic fuel, or in heating and electricity production. If the gas is used for heating or electricity production, it does not have to be purified. However, using biogas in heating or electricity production is not very profitable in some cases due to issues such as variation in demand (see also Lehtokunnas and Pyyhtinen, 2023). Further, the purification of biogas can be especially problematic for the plants:

> If a biogas plant wants to build infrastructure that would enable the purification of the gas so that it would contain over 98 percent methane, that would mean that the plant should be able to invest at least one million euros in the machinery. But for example, for a biogas plant the same size as our plant, it would mean that you should be able to invest two million euros to be able to purify all the produced gas. And if you want to distribute the gas for traffic use, you will need to build a refueling station network. For building this kind of network, you will, again, need to invest at least one million euros. If we think about the number of cars that currently run on biogas, these kinds of investments are not justified in any way. (Interview, May 2021)

This quote from the interview with the CEO of a biogas plant once again illustrates that generating monetary value in the context of biogas plants is by no means simple. Many plants do not have the possibility to invest in gas purification technology, not to mention gas distribution infrastructure. In the interviews, it was mentioned that some plants have no gas distribution infrastructure at all. In these cases, some of the gas is used for running the process of the plant, and the remaining gas is burned in a torch. Also other issues, such as variation in demand, may occasionally force the plants to torch part of the produced gas (see also Holmberg and Ideland, 2021; Lehtokunnas and Pyyhtinen, 2023).

Because of the problems related to distributing the end products and creating monetary value for them, Finnish and Swedish biogas plants do not get their income mainly from selling the products they produce but from the "gate fees" their customers pay them for treating their biowaste (see also Lehtokunnas and Pyyhtinen, 2023; Åkerman et al., 2020; Winquist et al., 2019). Moreover, the challenges of efficiently circulating gas are part of the indigestion embedded in the operation of the assemblage. The difficulties of circulating the gas and fertilizers show that, in many cases, it remains unclear whether the process of decay produces valuable end products or problematic excess (see Lehtokunnas and Pyyhtinen, 2023). Thus, the marketization of biogas and fertilizers depends on the preferences of multiple actors within the assemblage, such as farmers and energy markets. In this sense, encounter value production involves not only the encounters between microbes and plant workers that enable productive decay but also many other elements that shape the process of value creation.

It is still crucial to note that regardless of these problems, most of the gas produced at biogas plants is utilized in one way or another: Only 11 percent of the gas produced at Finnish plants is torched (Suomen biokerto ja biokaasu ry, 2023), while at Swedish plants, only 8 percent is torched (Energigas Sverige, 2025). Still, considering all the problems related to creating monetary value from biogas, and especially from fertilizers, a question arises: Does it currently make sense to think about the marketization of biogas and fertilizers through the lens of economic value production, or are other forms of value currently more central in the case of creating encounter value through microbial work at biogas plants?

While biogas and fertilizers do not currently create steady income streams for biogas plants, there still exists a strong political aim to invest in biogas technology as part of the efforts of striving for a CE. As the biogas industry creates a certain kind of digestive assemblage that is strongly shaped by the CE discourses of turning waste into value and creating economic growth, the apparent difficulties of creating economic profit through producing biogas and fertilizers are somewhat paradoxical. Based on our analysis, we argue that rather than focusing only on economic value production in the sense of creating a steady revenue stream through the practices of turning waste into valuable products, it is crucial to also pay attention to the symbolic value that the work of microbes has from the viewpoint of the CE. While the CE is often associated with ideas such as creating an economy that mimics natural processes (Skene, 2018), the symbolic value produced through the process of decay and microbial work becomes central both from the viewpoint of the marketization of biogas and fertilizers and the digestive assemblage in which biowaste is treated.

Discussion

In this article, our aim was to delve into the apparent paradox of value creation and ruination by studying decay as a productive process of microbial work in the context of biogas production. Through our analysis, we showed how value is produced in encounters between humans and microbes in the different stages of decay at Finnish and Swedish biogas plants. We have illustrated that rather than creating constant progress and growth in the context of the CE, the process of decay at biogas plants also entails problematic ruination and breakdown (Jackson, 2013) that must be tinkered with through different maintenance practices (Graham and Thrift, 2007). Our analysis revealed that although the process of decay can be made productive through microbial work, as well as various maintenance practices and technical solutions, the work of microbes also produces problematic materials, and value creation for the end products of the biogas production process is complex. We also showed how the digestive assemblage, through which biowaste is transformed into biogas, consists of multiple different actors that shape the assemblage both before the waste enters the plants and after the biogas production process has ended.

In the first analysis section, we examined the biowaste pretreatment process and showed how microbes, maintenance workers, and their repair practices are crucial to the digestive assemblage. However, our analysis illuminates how other actors in the assemblage may create indigestion at biogas plants: Plastic waste must be separated from biowaste and transported to incineration plants; thus, the digestive assemblage is also reliant on a wider waste infrastructure. Moreover, the outcomes of the production processes cannot always be controlled. The second analysis section examined how microbes work with biowaste that has been turned into slurry after the pretreatment process. Here, balancing between the productionist logic and the unruliness of microbial work became central to encounter value production. In the final section, we studied how the produced biogas and fertilizers are circulated and marketized. Here, it became apparent that encounter value production is not only about the encounters between humans and microbes within the biogas plant but also about other actors in the assemblage, such as farmers and energy markets, that shape the possibilities for the marketization of biowaste and fertilizers. In this section, our analysis showed that there are several problems in the practices of creating monetary value for the end products.

Our findings indicate that multiple problems complicate the achievement of efficient production and the marketization (Çalışkan and Callon, 2010; Pütz, 2021) of biogas and fertilizers in the context of the CE. The marketization of these products requires active work from human and nonhuman waste workers. However, this work can also complicate the possibilities for the marketization of the end products by creating indigestion in the process. Further, in addition to the fact that the work of human and nonhuman waste workers may complicate value creation and marketization processes, also other factors shape these processes. For example, the disruptions plastics cause at biogas plants are often considered less serious than the economic inefficiency that would result from requiring retailers and food industry businesses to remove plastic and other packaging from biowaste. Thus, it seems that the still dominant linear economic model and especially its ideals of economic efficiency clash with the waste treatment practices at biogas plants. From a policy perspective, our analysis provides insights into the entanglements of different waste streams and highlights the need to reduce plastic waste both in businesses and households.

Moreover, the fact that different waste batches may lead to issues such as the production of hydrogen sulfide and foaming indicates that the reality of microbial work may contradict the CE goals of treating all waste as ecologically and efficiently as possible. Also the difficulties of creating monetary value from the end products of the biogas process show that the problems of indigestion in the digestive assemblage do not only relate to issues such as plastics, foaming, or other undesirable outcomes of microbial work; indigestion also relates to the problems of the marketization of end products, as problems of marketization complicate the possibility of moving these products forward into new economic cycles.

These findings expand the social scientific discussion on value production (Greeson et al., 2020; Helgesson and Muniesa, 2013; Muniesa, 2012), especially by showing how the anthropocentric understandings about economic efficiency and value often overlook the role of multispecies workers, such as microbes that break down waste at biogas plants. Microbes cannot digest many materials that end up to biogas plants and that economic practices still produce excessively (e.g., plastics). Moreover, like all forms of value creation, encounter value production with microbes in the context of the CE creates excess (Greeson et al., 2020). This is often dismissed by the CE discourses that highlight fantasies such as the endless circulation of waste (Skene, 2018). Thinking about biogas production through the lens of digestive assemblages thus sheds light on the problems with the human-centered logic of production. While many kinds of actors are part of the digestive assemblage, so is the excess produced by different human and more-than-human actors. Thus, indigestion is a crucial part of the digestive assemblage. Managing this indigestion requires both being attuned to microbes and performing maintenance practices that, rather than create non-decay, embrace decay. Our findings also extend discussions on encounter value production by highlighting the complexity of value creation in the encounters between humans and different biological species.

This article also contributes to CE literature (Holmberg and Ideland, 2021; Lehtokunnas and Pyyhtinen, 2023; Hobson et al., 2021; Schulz et al., 2019) by complicating the ideas of (economic) value production in the context of the CE. In particular, the findings complicate the CE discourse that celebrates economic growth. We argue that other forms of value creation may on some occasions be more significant in the practical implementation of the CE. The problems related to the marketization of the end products of the biogas production process show that economic value production in the context of the CE is shaky. While the production of biogas and fertilizers is not always economically efficient, we argue that, in addition to economic value creation, symbolic value creation through the promise of endless circulation of waste is central to the biogas industry. However, as our analysis has shown, this perfect circulation of waste is impossible, as indigestion is always embedded in digestive assemblages. Biogas production may thus create an illusion of control over the enormous, destructive masses of waste that capitalist production and our current way of life produce. As Laporte has noted, “the incapacity of the system to manage its own filth is lucidly betrayed by its intrepid fantasy of an elimination so complete it leaves no trace of waste” (Laporte, 1993: 14).

In conclusion, by focusing on the process of decay as a mode of production, our findings indicate that, rather than separate processes, the processes of value creation and ruination are necessarily interconnected. Based on our analysis, we argue that to foster digestive assemblages in the age of current ecological crises, the possibilities of indigestion and “dyspepsia” (Haraway, 2008: 293) should also be taken seriously. This means that potential inefficiencies always inherent to the digesting systems should not be hidden under the productionist discourses and practices that celebrate the perfect elimination of waste, but the whole anthropocentric logic of the CE and production should be debated.

Highlights

- The microbial process of decay in anaerobic digestion at biogas plants can be understood as productive activity
- The circular economy discourse often highlights economic value over other values
- The value produced by microbes is not necessarily mainly economic but, rather, symbolic
- Understanding decay as a mode of production enables critically assessing the human-centered concept of production in the context of the circular economy

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