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Management**

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and Social Sciences (BMS)**

**Assessment of
Biodegradable Plastic
Waste Management
in Leeuwarden**

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Abstract

Biodegradable plastics have emerged as a sustainable alternative to conventional plastics with the potential to reduce plastic waste as well as contribute to the circular economy. However, improper disposal practices can offset their environmental benefits. As the production of these plastics continues to grow, it becomes crucial to ensure effective management of biodegradable plastic waste.

This study assesses the inefficiencies in the biodegradable plastic waste management system in Leeuwarden from a socio-technical perspective. The study utilized a mixed methods approach through resident surveys and stakeholder interviews to gain a comprehensive understanding of the system from diverse perspectives, providing key insights into the system's strengths, inefficiencies and the complex interactions between various components of the system. The study identified various strengths such as active separation of waste, resident engagement and adaptive capacity of the system to evolve over time.

However, there are significant challenges hindering the effective waste management of biodegradable plastics; such as knowledge gaps and improper disposal practices among residents, an underdeveloped technical infrastructure and value chain for biodegradable plastics, a lack of regulations and absence of producer incentives. Optimizing the system requires efforts in various domains including public awareness campaigns, improved labelling with clear disposal instructions, policy interventions, stakeholder collaborations and infrastructure development for sorting, composting and recycling. Addressing the inefficiencies of the system is crucial as the production of biodegradable plastics is projected to increase in the coming years.

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1. Introduction

With the increase in global production of plastics over the last two decades, the amount of plastic waste generated has doubled from 156 million tons in 2000 to 353 million tons in 2019 (Lee et al., 2024). Plastic waste can pose a serious threat to the environment, with inadequate waste management resulting in the accumulation of these plastics in the environment. This results in the release of chemicals and microplastics into the environment, which can cause significant damage to ecosystems and their biodiversity (Afshar et al., 2024; Lee et al., 2024; Cazaudehore et al., 2022).

Biodegradable plastics have emerged as a sustainable alternative to conventional plastics, reducing the use of fossil fuels and lowering greenhouse gas emissions during their life cycle (Moshood et al., 2022). As a response to environmental concerns, several products made with single-use non-biodegradable plastics have been banned in several countries within Europe. Simultaneously, many countries are increasingly adopting biodegradable plastics due to their degradability (Afshar et al., 2024; Cazaudehore et al., 2022). Biodegradable plastics are thus becoming increasingly seen as a potential solution to combat the global crisis of plastic pollution and its detrimental effects (Mut et al., 2024; Liao & Chen, 2021; Afshar et al., 2024).

However, the effective biodegradation of biodegradable plastics depends on their material properties, the use of additives in their production and specific environmental conditions such as temperature, moisture, pH and other abiotic factors (Mut et al., 2024; Afshar et al., 2024; Liao & Chen, 2021). If improperly disposed, these plastics can enter the open environment and contribute to plastic litter or waste. Additionally, some studies show that biodegradable plastics can fragment into microplastics in natural environments, contributing to soil and water pollution (Afshar et al., 2024; Mut et al., 2024). Thus, the improper disposal of biodegradable plastics can offset their environmental benefits. It is therefore vital to ensure proper end-of-life management of these plastics.

The production capacity of biodegradable plastics is projected to significantly increase from approximately 1.13 million tonnes in 2023 to 4.6 million tonnes in 2028, as illustrated in Figure 1 (European Bioplastics, n.d.-b). Furthermore, the global market value is forecasted to increase threefold, growing from 5.28 billion U.S. dollars in 2022 to 14.43 billion U.S. dollars by 2030 (Statista Research Department, 2024).



Figure 1: Global production capacities of biodegradable plastics in 1,000 tonnes (European Bioplastics, n.d.-b).

While the production of biodegradable plastics is unlikely to overtake conventional plastics in the near future, a growing awareness among policy makers and consumers about the finite availability of fossil fuels and the need to reduce their environmental impact has led to a reevaluation of plastic production and usage in daily life (Filho et al., 2021; Iwata, 2015 as cited in Cazaudehore et al., 2022). Simultaneously, the use of biodegradable plastics is expected to grow in the existing plastic ecosystem due to various factors such as increasing public interest and annual demand, use of non-fossil feedstock and their potential for biodegradability-required applications (Moshood et al., 2022). As the production of these plastics continues to grow, assessing and optimizing current waste management systems thus becomes crucial to ensure responsible management of biodegradable plastic waste.

While there exists research on waste management, only a limited number of studies have looked at waste management by studying its socio-technical aspects, leaving a gap in research (Andersson et al., 2019; Nurdiawati & Agrawal, 2022; Liu et al., 2023), particularly in the area of biodegradable plastic waste management through a socio-technical systems approach. The socio-technical systems perspective emphasizes that the social, technical and environmental components of a system are interconnected and cannot be optimized individually, advocating for a holistic analysis to improve system performance (Abreu Saurin & Patriarca, 2020; Manny et al., 2022). This thesis aims to bridge this research gap and assess the effectiveness of the biodegradable plastic waste management system in Leeuwarden through a socio-technical perspective so as to identify inefficiencies within this system and optimization strategies.

The thesis aims to study the waste management system by exploring the social and technical sub-systems. It examines the social sub-system, focusing on resident awareness and behaviour regarding biodegradable plastics. Concurrently, it explores the technical sub-system, examining the processes and technologies for collection, sorting and processing biodegradable plastic waste. By studying these sub-systems and the interactions between them, the research aims to identify the strengths and inefficiencies of the waste management of biodegradable plastics in Leeuwarden.

1.1 Rationale for Case Study Selection

This research focuses on the city of Leeuwarden, Netherlands with a population of 128,858 inhabitants (Gemeente Leeuwarden, n.d.-b); serving as a case study to explore the socio-technical aspects of biodegradable plastic waste management within the context of a medium-sized urban center. Leeuwarden has a strong vision for a circular economy and a commitment to reducing waste. For example, it has ambitious goals of reaching only 30 kg of residual waste per resident per year by 2030 and becoming a waste-free district by 2050 (Gemeente Leeuwarden, n.d.-a). Thus, Leeuwarden provides a valuable case study for understanding waste management in urban areas, with its medium size providing a manageable scope for research. Furthermore, its strong commitment towards a circular economy and waste reduction goals make the findings of this research potentially relevant for the city's sustainable objectives.

1.2 Research Objective

The main objective of this research is to assess the effectiveness of the waste management of biodegradable plastics in Leeuwarden; by mapping and elucidating the journey of biodegradable plastics from resident awareness and behaviours to waste treatment by waste management companies, and then identifying and analyzing any inefficiencies or failure points within this socio-technical system that hinder the effective management of biodegradable plastics. Identifying such

inefficiencies can then provide valuable insights into areas of the system that can be better optimized for effective management of biodegradable plastic waste.

Some overarching areas of focus explored within this research are as follows:

- *Resident awareness and knowledge*: This area explores the current state of resident knowledge and understanding regarding biodegradable plastics. It explores residents' awareness of the differences between biodegradable, bio-based and bioplastics, as well as their ability to recognize biodegradable plastic labels. Additionally, it delves into their knowledge about effective disposal methods for biodegradable plastics.
- *Resident behaviour*: This area involves exploring behaviours of residents and how they dispose of biodegradable plastics.
- *Waste management processes and technologies*: This area explores the provision of adequate collection points provided by waste management companies, the sorting techniques used to separate biodegradable plastics from other plastic waste streams and the processes or technologies utilized for the treatment of biodegradable plastics.
- *Stakeholder relations and collaboration*: This area delves into the communication strategies and channels used by waste management companies to communicate with residents, and the effectiveness of these means of communication. It involves exploring how residents can provide feedback and how their feedback is incorporated into improving the system.

These social and technical aspects of the biodegradable plastic waste management system serve as a guideline for the research process, guiding the data collection and analysis phases of the research.

1.3 Research Questions

The main research question for this study can be formulated as:

What are the inefficiencies or failure points in the waste management of biodegradable plastics in Leeuwarden from a socio-technical systems perspective?

The four sub-questions that this research aims to address are as follows:

- **R1**: What does the current waste management system of biodegradable plastics in Leeuwarden look like, considering the social and technical aspects of this socio-technical system?
- **R2**: What are the strengths of the current biodegradable plastic waste management system?
- **R3**: What are the identified inefficiencies or failure points within the current system from the perspectives of the various actors operating in this system?
- **R4**: How can the current waste management system be transitioned or redesigned into a more optimal system?

These sub-questions aim to address various aspects of the main research question to gain a comprehensive understanding of the waste management of biodegradable plastics in Leeuwarden. To achieve this, the first sub-question involves studying the current or existing biodegradable plastic waste management system by exploring the social and technical factors and the interactions between them. This exploration delves into resident awareness and disposal behaviours, technical processes, collaboration and communication channels between stakeholders; guided by the overarching areas of

exploration provided earlier in the introduction. The perspectives and insights gained can then help address the second and third sub-questions.

According to a report by the Global Compact Cities Programme (2015), waste management and reduction as well as waste management infrastructure are stated as Leeuwarden's strengths in terms of city sustainability. This inspired the second sub-question which focuses on identifying the strengths and successful aspects of the biodegradable plastic waste management system, which can be further leveraged for optimization. The report further mentions that solid waste management is of moderate concern, which indicates there are some possible limitations of the system. The third sub-question involves identifying the inefficiencies and failure points of the existing biodegradable plastic waste management system by exploring the perspectives of various actors involved such as residents, waste management companies, the municipality, etc. Doing so can help identify aspects of the system that are improperly functioning or not as optimally. The fourth sub-question takes a solution-oriented approach by exploring potential opportunities or strategies for optimizing the system.

1.4 Report Outline

The remainder of this report is structured as follows: Section 2 describes complexity theory and socio-technical systems (STS), and summarizes the literature on waste management of biodegradable plastics from technical, social and policy perspectives. Section 3 outlines the research methodology, providing a detailed account of the data collection and analysis methods. Section 4 presents the findings from resident surveys and interviews with stakeholders along the biodegradable plastic value chain, describing the current biodegradable plastic waste management system in Leeuwarden. Section 5 analyzes these findings to identify strengths and inefficiencies of the system, which then informs strategies for optimization. The section then explores the limitations of this thesis and provides suggestions for future research. Finally, Section 6 concludes the report by summarizing the findings.

2. Literature Review

This section presents a literature review on Complexity Theory, followed by an examination of the Socio-Technical Systems (STS) theory, which serves as the theoretical framework for this research. Analyzing waste management systems through the lens of the STS framework provides a thorough understanding of their social and technical aspects and the interactions between them. This holistic perspective is crucial for assessing waste management systems effectively. The literature review then delves into the current state of research on waste management of biodegradable plastics. By understanding current practices and challenges, the review sets the groundwork for assessing the waste management of biodegradable plastics in Leeuwarden.

2.1 Theoretical Framework

2.1.1 Complexity Theory

In contrast to reductionistic approaches in which a system is reduced to its sub-parts, whereby the complexities of the whole cannot be captured; complexity theory looks at systems as complex systems where its parts interact with each other and these interactions result in new emergent properties or states, which cannot be understood by studying the individual parts of the system. To understand these emergent phenomena, the system as a whole must be studied together with its components and their interactions over time (Turner & Baker, 2019).

Complexity theory has four fundamental principles:

- Chaotic behaviour or non-linearity: Complex systems can be unpredictable due to their sensitivity to initial conditions and can thus behave in chaotic ways. Even small changes in one part of the system can have rippling effects on other parts of the system, leading to positive or negative outcomes that are significant different from what was initially intended (Murray, 1998).
- Complex adaptability: Individuals and groups within a complex system tend to adapt to each other and the environment with which they interact with. Given clear direction and purpose, actors within the system learn from success and reinforce past successful behaviours and actions, which creates a positive feedback loop. Beyond reinforcing past successes, adaptation can also entail shaping the environment in creative ways to achieve their strategic purpose (Murray, 1998).
- Self-organization: Complex systems exhibit emergent behaviour, where the behaviour of the whole system cannot be predicted solely on the behaviour of its parts or sub-systems. Within such systems, people can organize themselves in ways that they believe will lead to success; which can lead to outcomes that were unanticipated by top-down management. Also, power dynamics and vested interests of actors can impact self-organization (Murray, 1998).
- Co-evolution: Complex systems do not reach a stable equilibrium state as they are continuously evolving and developing due to its adaptable nature, though not necessarily always in a progressive path. Complex systems co-evolve with other organizations or groups, wherein both influence each other (Murray, 1998).

To understand such complex systems, the complexity theory provides 'Complex Adaptive Systems' as a framework for studying these systems (Turner & Baker, 2019). Thus, in line with the above principles, complex adaptive systems are open, dynamic systems that are capable of self-organization through the exchange of information, energy, resources and other interactions with their environment. In response

to the environment's pressures, they are constantly changing and evolving, and learning and adapting, resulting in emergent properties (Turner & Baker, 2019). Complexity science has gained prominence across various disciplines due to the limitations of traditional mechanistic approaches and the growing complexity of modern socio-technical systems (Soliman & Saurin, 2017). Complex socio-technical systems are a class of complex adaptive systems (Soliman & Saurin, 2017); where the concept of complex adaptive systems with dynamic interactions between components, emergent properties and continual learning and adaptation provides valuable insights for understanding socio-technical systems (Bauer & Herder, 2009). Thus, the principles of complexity theory can be applied to waste management systems that are complex socio-technical systems.

According to McGill et al. (2021), several studies highlight that a complex systems perspective can enable better understanding of the complex nature of real-world environments. While complex systems are challenging to fully understand or manage, this systems perspective allows researchers and stakeholders analyze system behaviour and identify ways to guide it towards more desirable behaviour patterns or outcomes (Meadows and Wright, 2008 as cited in McGill et al., 2021).

2.1.2 Socio-Technical Systems (STS) Theory

Socio-technical systems refer to systems that involve complex interdependencies and interactions between people and machines within the context of the environment that they're operating in (Liu et al., 2023). While the social and technical sub-systems are distinct systems following the laws of human and natural sciences respectively, they are interdependent relying on each other for the transformation of an input to an output which is the core function of any system (Trist, 1981). Trist emphasizes the need for joint optimization of the social and technical sub-systems to achieve desired outcomes, as optimizing only one of these systems would lead to the sub-optimization of the whole system. Eason (2014) stresses the important role of the social sub-system by highlighting that even if the technical system is designed without considering the social system, it's user behaviour and how people interact with the technical sub-system that determines overall system effectiveness. They are the 'defacto' designers of the system. The potential benefits of the technical system cannot be fully realized unless its capabilities are utilized by the social system to achieve a goal (Eason, 2014). This highlights that it is not enough to optimize the technical sub-systems of a socio-technical system, it should also jointly incorporate the optimization of the social sub-system.

According to Trist (1981), STS studies can be conducted at the levels of primary work systems, whole organization systems and macro-social systems. Primary work systems refer to systems that perform tasks within a well-defined sub-unit of an organization. Moving beyond primary work systems, whole organization systems refer to the entire organizations such as plants, independent workspaces, corporations and public agencies. Macro-social systems include systems in communities and institutions that function at a societal level (Trist, 1981).

Considering the macro-social level, waste management is a complex socio-technical system that serves a societal function. It involves complex interactions between human behaviours, practices and lifestyles and physical waste infrastructure and technologies (Duygan et al., 2018; Zacho et al., 2018). These physical infrastructure and facilities are not stand-alone structures, they require the active involvement of various societal actors. The effectiveness of such infrastructure depends on the behaviours and habits of individuals utilizing these facilities. Waste management infrastructure, in turn, influences the social habits of people using this infrastructure and the way they handle waste streams. Thus, this waste management socio-technical system consist of separate physical facilities and social actors that are linked through waste streams and waste treatment processes; and the performance and

effectiveness of this socio-technical system depends on the joint optimization of its social and technical sub-systems (Liu et al., 2023).

The socio-technical system (STS) framework incorporates the idea of design incompleteness, emphasizing the need for continual review and revision of system designs and application of its principles to new challenges (Davis et al., 2014). Biodegradable plastics add new challenges to already complex waste management systems, thus requiring an STS approach to assess the existing systems and adapt them for optimal functionality. An STS approach applied to the waste management system in Leeuwarden can help assess how social factors like resident knowledge and behaviours interact with technical factors like collection infrastructure and sorting facilities, and how these interdependencies can influence effective biodegradation of biodegradable plastics.

2.2 Waste Management of Biodegradable Plastics

Biodegradable plastics are seen as the sustainable alternative to conventional plastics as they can decompose into harmless substances. However, numerous studies highlight that biodegradation of these plastics occurs only under specific environmental conditions such as temperature, pH, moisture, oxygen content, abiotic factors, polymer characteristics (Shen et al., 2020; Mut et al., 2024; Afshar et al., 2024). This makes achieving biodegradation of these plastics in the natural environment difficult. Additionally, when compared to conventional plastics, biodegradable plastics can more easily fragment into microplastics under partial degradation and their additives used during production can leach into the environment (Afshar et al., 2024). Another significant challenge when it comes to biodegradable plastics is landfill disposal. When these plastics are buried in landfills and undergo anaerobic decomposition without adequate gas capture technologies, they can release a significant amount of greenhouse gases like methane and carbon dioxide, thus having the potential to cause significant harm to the environment (Park et al., 2024). These limitations highlight the critical importance of effective waste management strategies of biodegradable plastics.

2.2.1 Waste Management from a Technical Perspective

Unlike traditional plastics, biodegradable plastics can be efficiently broken down under specialized treatment methods. These are anaerobic digestion and composting; both of which utilize microorganisms to decompose biodegradable plastics into methane, carbon dioxide and organic matter (Park et al., 2024). Usually plastics used in food packaging are not recycled due to contamination and often incinerated or sent to landfill. Anaerobic digestion offers a potential waste management method for treating biodegradable plastics particularly those used for food packaging as biodegradable plastics and food waste can be treated together to produce biogas which is an energy source and digestates that can be diverted into composting material (Park et al., 2024). However, this waste treatment has limitations. It's not easy to distinguish biodegradable and fossil-fuel based plastics, which requires specific methods to sort the different plastic types. Additionally, studies by Park et al. (2024) and Cazaudehore et al. (2022) show that not all biodegradable plastics are easily biodegraded under anaerobic conditions and can fragment into smaller plastics in the digestates and also contaminate the biogas.

The other waste treatment method is composting, where microorganisms break down biodegradable plastics under aerobic conditions (i.e. in the presence of oxygen) into carbon dioxide and compost. Industrial composting takes place under conditions of high temperatures ranging from 50–60 °C, adequate oxygen and moisture (Park et al. 2024). They offer the advantage of diverting biodegradable plastics away from landfills. However, there are some limitations. Many composting facilities are

currently designed to degrade organic waste like food and yard waste, and are not equipped to handle biodegradable plastics which require specific conditions of high temperature and moisture that may not be available at all composting sites. These limitations indicate the challenges of introducing biodegradable plastics in industrial composting sites. However, composting is still considered as a valuable end-of-life treatment option for biodegradable plastics.

Thus, the limitations in these waste treatment methods of biodegradable plastics highlight the need for improved sorting technologies to distinguish biodegradable plastics from other plastics, research into development of biodegradable plastics with faster or more complete biodegradation rates and the optimization of biodegradable plastic waste management treatments of anaerobic digestion and industrial composting (Cazaudehore et al., 2022; Park et al., 2024).

2.2.2 Waste Management from a Social Perspective

In addition to the technical infrastructure, systemic and social-technical approaches are needed for effective waste management (Andersson et al., 2019). While biodegradable plastics have the potential to reduce the environment impact of traditional plastics, it is very much contingent on proper disposal by users such as placing them in the correct bins and adequate post-consumer management such as collecting them in the correct waste streams and processing them under the specific conditions required for biodegradation (Allison et al., 2021). A few studies conducted in UK and Germany have shown that even though people have positive attitudes towards biodegradable plastics, they disposed them incorrectly due to lack of knowledge and awareness, thus wasting potential gains from their biodegradability.

The behaviours of various actors such as residents, suppliers, retailers, policy makers, etc. play a role in the generation of plastic waste across various stages of production, supply, use and waste collection and processing of plastics. Thus, behavioural change is a key component of optimizing the plastics system and reducing plastic waste (Allison et al., 2021). Allison et al. (2021) further highlights that citizen behaviour is an integral part of this plastics systems, more specifically through their purchasing, use and disposal decisions. The study by Allison et al. (2021) explores factors influencing citizens' choices regarding biodegradable and compostable plastic packaging. While the study focuses on purchasing decisions, it can also provide insight into waste disposal behaviours of users. A significant challenge identified in the study is a lack of awareness or confusion around packaging labels, environmental impacts and end-of-life instructions regarding biodegradable plastics. According to the European Union, there is wide spread confusion among consumers about different types of plastic labels. Users also stated a lack of knowledge about disposal options and waste collection systems available to them. The absence of a standardized collection and waste treatment system for biodegradable plastics can worsen issues of littering or contaminating of other waste streams. Thus, a proper labelling system and an efficient biodegradable waste collection and treatment system is needed to tackle these problems (Allison et al., 2021).

According to Pedersen & Manhice (2020), waste separation is still not implemented as a widespread practice in EU households. While numerous studies highlight that individuals' awareness, attitudes and sustainable values play a role in waste separation behaviour, Pedersen & Manhice (2020) state that these characteristics are not the only drivers to pro-environmental behaviour. Despite having positive intentions, effective waste management relies on time constraints and whether waste separation competes with existing household obligations and routines such as cooking and cleaning. Another barrier identified by the study by Pedersen & Manhice (2020) was the inconvenience of extra effort required to properly sort waste or separate hard-to-handle waste such as biowaste. Thus, apart from

awareness and education campaigns, waste management infrastructure and policies should also take into account the practicalities and costs of daily life.

Additionally, Pedersen & Manhice (2020) highlight a structural mismatch between the technical waste management system and user understanding or interpretation around information and accessibility to disposal. They suggested making different categories of collection bins easily distinguishable, providing easily accessible residual waste bins and strategic placement of waste bins. These highlight a need to re-design the technical waste management infrastructure at the points of user interaction for optimal waste separation and disposal, contributing to a more efficient waste management system.

The successful adaptation of waste management systems will require a balanced approach taking into consideration policy requirements, waste management infrastructure and households (Ordoñez et al., 2015 as cited by Pedersen & Manhice, 2020). This further emphasizes the importance of looking at biodegradable plastic waste management from a social and technical lens. Hence, this research will use the Socio-Technical Systems (STS) framework to assess the waste management of biodegradable plastics in Leeuwarden by examining the social and technical systems and the interplay between them.

2.2.3 Waste Management from a Policy Context

The EU's Waste Framework Directive (WFD) introduced a waste hierarchy in the waste management system in 2008, whereby the first priority should be prevention of generation of waste, after which the generated waste should be reused, recycled or recovered and the remaining non-recyclable waste must be incinerated or sent to landfills (Liu et al., 2023; European Union, n.d.-b). Biodegradable plastics can add a new level of complexity into this waste hierarchy.

The EU policy framework on biobased, biodegradable and compostable plastics encourages the use of biodegradable plastics in line with circular economy and waste hierarchy principles when it is no longer possible to reuse and recycle (European Union, n.d.-a). It also emphasizes that labelling standards of biodegradable should not confuse consumers, causing them to dispose them in ways that cause "plastic littering or pollution due to unsuitable environmental conditions or insufficient time for degradation" (Food and Agriculture Organization of the United Nations (FAO), 2023).

However, there are currently no legally binding laws or regulations that apply to biodegradable plastics (European Union, n.d.). Additionally, science-based testing and certification standards of biodegradable plastics are still to be developed (FAO, 2023). These lack of regulations and quality assurance standards further complicates the effective production, use and especially end-of-life treatment of biodegradable plastics.

3. Methodology

This section outlines a schematic representation of the biodegradable plastic waste management system in Leeuwarden. It then provides an overview of the methodological approach of the research process, followed by a detailed explanation of the methods for data collection and data analysis.

The following Figure 2 presents a schematic diagram representing an initial understanding of the biodegradable plastic waste management system in Leeuwarden, as viewed through the lens of the Socio-Technical Systems (STS) framework discussed in Section 2.1.2 of the literature review. The socio-technical systems perspective enables a holistic study of the waste management system by examining its sub-systems and the various interactions and interdependencies between the social and technical aspects. The diagram illustrates the system boundary, highlighting the social and technical sub-systems of the biodegradable plastic waste management system, and the possible interactions between the various social and technical components within this system. The social sub-system consists of the actors involved in the waste management system in Leeuwarden such as residents, the waste management company and the municipality. The technical sub-system consists of the physical waste infrastructure such as collection points, sorting centres and the treatment facilities. This sub-system also includes the treatment processes for biodegradable plastic waste. This socio-technical system is further embedded within the biodegradable plastic value chain system, influenced by industry and policy.

This schematic diagram of the socio-technical system was initially inspired by the visual elements of the social and technical sub-systems embedded within the larger complex environment as presented in Oosthuizen & Pretorius (2016). Nevertheless, the diagram presented here was created independently to illustrate the primary stakeholders, the technical infrastructure and processes, and various potential interactions and flows specific to the biodegradable plastic waste management system in Leeuwarden. While a conceptually similar representation of municipal waste management system was found in Liu et al. (2023), these similarities are due to the common elements found in socio-technical and waste management systems. The diagram presented in this study highlights the specific actors or agents within the social sub-system, and the specific infrastructure and potential waste treatment options (as identified in literature) within the technical sub-system. Additionally, it places the biodegradable plastic waste management system within the larger biodegradable plastic value chain, providing a holistic picture of the socio-technical system from a broader context.

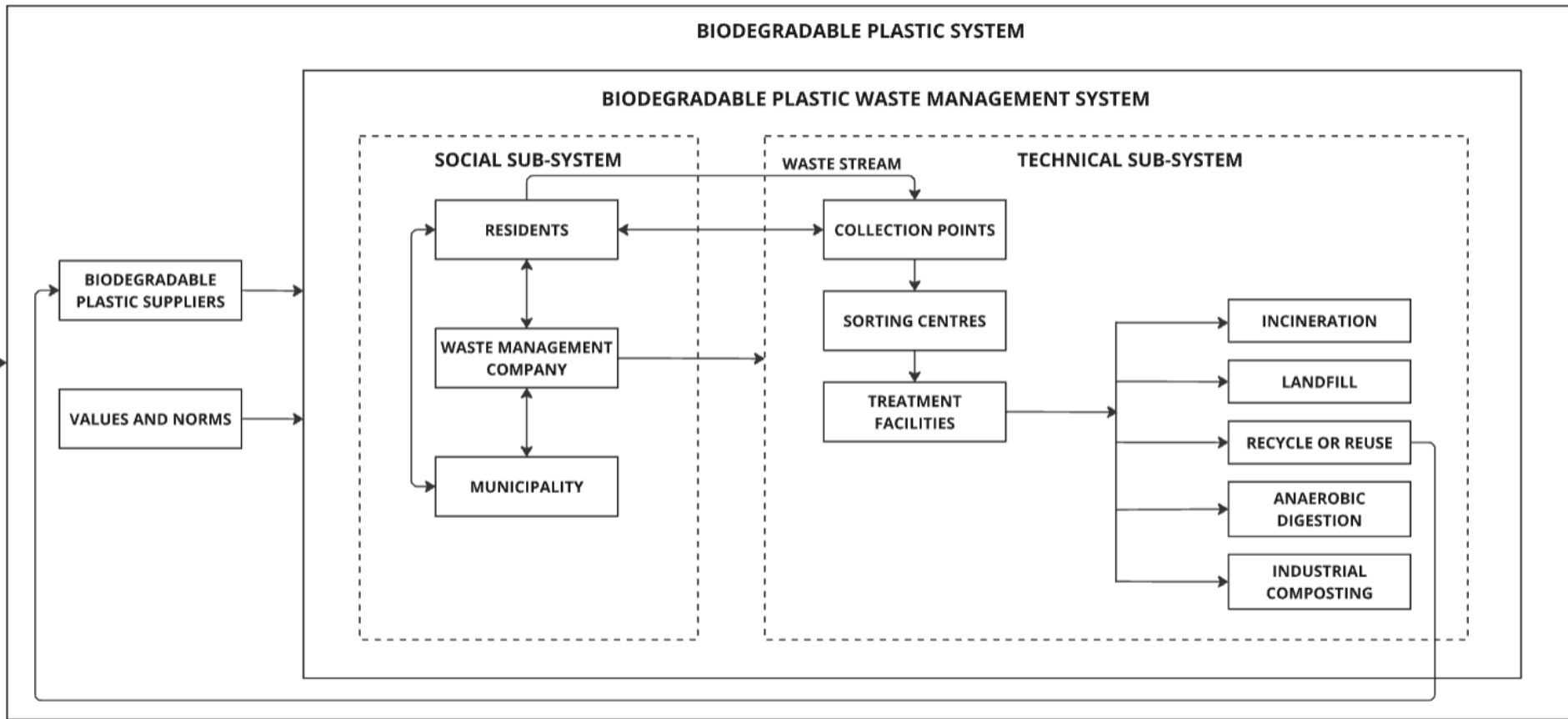


Figure 2: Schematic diagram of biodegradable plastic waste management system in Leeuwarden with its social and technical sub-systems
(Source: Author)

3.1 Mixed Methods Approach

A mixed methods approach integrating quantitative and qualitative data collection and analysis methods was used to gain a comprehensive understanding of the social and technical aspects of the biodegradable plastic waste management system, and their interactions with each other. According to Creswell & Plano Clark (2007, as cited in Molina-Azorin, 2016), the combined use of quantitative and qualitative approaches enables a better understanding of research problems and complex phenomena than using either approach alone. In the same vein, Bigler et al. (2019, as cited in Strijker et al., 2020) states “the use of mixed methods is almost inevitable when taking a holistic view to tackle a research problem. This is because reality is, in general, too complex to be approached one-dimensionally”. Thus, the mixed methods strategy is well-suited for studying a complex, multi-faceted system such as the biodegradable plastic waste management systems with its social and technical sub-systems, its various stakeholders, their interdependencies and interactions with these systems, thus aligning with the socio-technical systems (STS) framework.

This mixed methods approach enabled engagement with a diverse range of stakeholders; allowing a thorough examination of the research question from multiple perspectives (Regnault et al., 2018). The study involved primary data collection with surveys distributed to residents and interviews conducted with diverse stakeholder groups. The quantitative method provided a larger data set of resident perspectives and behaviours; while the qualitative method captured in-depth insights and perspectives of various stakeholders within the biodegradable plastic waste management system in Leeuwarden and various actors in the value chain of biodegradable plastics. Quantitative methods alone would not capture the depth of stakeholder perspectives whereas solely using qualitative methods would not provide the breadth that a large dataset offers. This study utilized a concurrent design, whereby quantitative and qualitative data was collected and analyzed in parallel (Molina-Azorin, 2016). Triangulating these data sources facilitated a deeper understanding of the current system, highlighting its strengths, inefficiencies and areas for improvement. As noted by Watkins & Giola (2015, as cited in Strijker et al., 2020), triangulation has evolved as a means to approach a social phenomenon from different perspectives to gain insights into it. Strijker et al. (2020) further adds that triangulation captures and does justice to social reality rather than solely validating results.

The following Table 1 provides an overview of the research sub-questions, the sources and the methods for collecting data in order to answer these questions.

Table 1: Overview of sub-questions, desired information, sources and assessing method for answering the research questions

Sub-Question	Desired Information	Sources	Accessing Method
R1: What does the current waste management system of biodegradable plastics in Leeuwarden look like, considering the social and technical aspects of this socio-technical system?	Resident awareness and knowledge, resident separation and disposal behaviours, perceptions of waste management companies, provision of collection points, plastic waste sorting techniques, technologies or treatment methods and composting facilities for biodegradable plastics waste	People: Residents, waste management industry professionals, municipality representatives; Municipality website; Waste management companies reports	Surveys, video conferencing interviews, descriptive analysis, thematic analysis

R2: What are the strengths of the current biodegradable plastic waste management system?	Identify strengths and successful components of the waste management system of biodegradable plastics from the perspectives of key actors	People: Residents, waste management industry professionals, municipality representatives; Municipality website; Waste management companies reports	Surveys, video conferencing interviews, descriptive analysis, thematic analysis
R3: What are the identified inefficiencies or failure points within the current system from the perspectives of the various actors operating in this system?	Identify inefficiencies or failure points in the waste management system of biodegradable plastics from the perspectives of key actors	People: Residents, waste management industry professionals, municipality representatives; Municipality website; Waste management companies reports	Surveys, video conferencing interviews, descriptive analysis, thematic analysis
R4: How can the current waste management system be transitioned or redesigned into a more optimal system?	Identify rooms for improvement, strategies to optimize the waste management system of biodegradable plastics	People: Residents, waste management industry professionals, municipality representatives; Scientific literature; Environmental Design Framework; Case studies of best practices	Surveys, video conferencing interviews, descriptive analysis, thematic analysis

3.2 Data Collection

The following section outlines the data collection methods and processes utilized in this study. The data collection process started with stakeholder engagement in the biodegradable plastic waste management chain in Leeuwarden. The primary stakeholders included residents in Leeuwarden, the waste management company personnel and the municipality. Surveys were carried out among residents while interviews were held with representatives from the waste management company and the municipality.

Resident Surveys

Semi-structured surveys were conducted with Leeuwarden residents aged 18 and above. The survey was designed with close and open-ended questions to gather information about residents' awareness, knowledge, separation and disposal practices regarding biodegradable plastics. The survey also aimed to gather residents' insights into the barriers, challenges and improvements for efficient disposal and waste management of biodegradable plastics. The survey consisted of fifteen questions; two Likert scale questions and thirteen multiple choice questions (eight single answer and five multiple answer), six of which included options for open-ended responses. Additionally, demographic information such as age, gender and household type was collected to understand the characteristics of the respondents. The complete list of survey questions can be found in Appendix A. The surveys took an average of 8 minutes to complete.

The primary method of data collection involved distributing paper-based surveys provided in both English and Dutch languages. Furthermore, an online survey was made available to obtain additional responses. Taking into account Leeuwarden's population size of 128,858 inhabitants, a 95% confidence level and a margin of error of +/- 5%, the sample size was 384 residents, which was computed using various online sample size calculators (including Raosoft sample size calculator). A total of 412 residents participated in the survey; this substantial sample size ensures greater reliability of the findings.

Given the time constraints of the thesis, a convenience sampling method was utilized as the most practical way to reach a large number of residents. Surveys were distributed in various public spaces such as the city centre, the town hall, public libraries and parks. Additionally, data was collected at university libraries, community centres and a swimming pool location visited by families with children from different areas of Leeuwarden. Furthermore, surveys were conducted at a sustainability market at the town hall after gaining permission from the municipality; where data was gathered from local farmers, food producers, vendors of locally produced goods and residents from different parts of Leeuwarden. These locations were selected to capture a diverse range of respondents within the limitations of convenience sampling. Data collection occurred at these locations over a period of four weeks with visits on multiple days and at different times to reach a wider audience; thus ensuring a slightly more balanced sample (Galloway, 2005; Stratton, 2021). Additionally, efforts were made to include participants across various gender and age groups especially men and older age groups. This approach introduced purposive sampling within the broader convenience sampling method to ensure a more balanced demographic profile (Galloway, 2005). The gender and age distribution of participants is provided in Table 2. While these measures aimed to introduce randomness and diversity and thus mitigate potential biases, it is important to note that convenience sampling can still result in some bias. The sample population may not be representative of the entire population and thus the findings of the survey may not be fully generalized (Andrade, 2021; Stratton, 2021). Nevertheless, the large sample size of 412 residents together with a diverse demographic profile can provide valuable insights into the biodegradable plastic waste management system in Leeuwarden.

Table 2: Demographic distribution of survey participants

Demographic Category	Survey Demographic Profile	Leeuwarden’s Demographics
Gender	Male (46%)	Male (50%)
	Female (53%)	Female (50%)
	Non-binary (1%)	Non-binary (Not specified)
Age Group	18-24 years (19%)	18-24 years (14%)
	25-34 years (23%)	25-34 years (18%)
	35-44 years (19%)	35-44 years (14%)
	45-54 years (9%)	45-54 years (14%)
	55-64 years (15%)	55-64 years (15%)
	65-74 years (11%)	65-74 years (13%)
	75 years or older (5%)	75 years or older (11%)
<p><i>Note: The percentage calculations for the survey’s gender and age demographics are based on responses of participants who provided these details. Participants who opted out of providing this information were not included in the percentage calculation.</i></p> <p><i>Leeuwarden’s demographic percentages were calculated based on data from Gemeente Leeuwarden (n.d.-b). Residents under the age of 18 were excluded from the calculations to ensure a more accurate comparison with the survey demographics.</i></p>		

Stakeholder Interviews

Semi-structured interviews were conducted with relevant stakeholders such as waste management company personnel and municipality representatives to gain in-depth insights into the existing biodegradable plastic waste management system within Leeuwarden. The interview questions for the waste management company (responsible for waste collection and sorting) were designed to gather

information on the current state of biodegradable plastic waste stream; existing infrastructure, processes and technologies for collection, sorting and treatment; and available treatment options. The questions also aimed to gain insights into the challenges and potential areas for improvement in the biodegradable plastic waste management system. Interviews were conducted with waste management company personnel from different functional areas to gather diverse perspectives within the organization, thus helping to mitigate any potential biases. Interviews with the municipality representatives aimed to understand any existing policies and regulations, resident engagement and collaboration with the waste management company.

In addition to Leeuwarden’s stakeholders, interviews were conducted with various stakeholder groups within the Netherlands such as waste processing facilities, biodegradable plastic producers, plastics recycling companies, industry associations and researchers. These interviews aimed to gain additional insights into the value chain of biodegradable plastics from a broader context. Gathering the insights of different stakeholders aimed to ensure a more balanced perspective and prevent the research from being too skewed towards the perspectives of the waste sector. The Table 3 provides a list of interview participants. The rationale for each stakeholder groups is further elaborated in Table 4, which appears later in this data collection section. Furthermore, email correspondence with a Dutch government agency provided additional clarification on relevant policies and regulations.

Interviewees within these key stakeholder groups were selected using purposive and snowball sampling methods, which ensured that interviews were conducted with individuals having relevant expertise and experience within the waste management system. Contact was initiated through LinkedIn, the networking platform widely used in the Netherlands. A total of nine interviews were conducted over a period of six weeks via Microsoft Teams, each lasting an average of 45-60 minutes. Interviews with each stakeholder group followed an interview guide, while allowing flexibility to adapt questions to the flow of the conversation. This approach allowed a deeper exploration of specific insights or themes emerging from interviewee responses. As highlighted by Magaldi & Berler (2020), a key characteristic of semi-structured interviews is the flexibility it offers the interviewer to follow different avenues of inquiry as information emerges, and adjust the sequence of questions, while adhering to the core topic focus outlined in the interview guide. The complete list of interview questions for each stakeholder group is provided in Appendix B. Follow-up interviews were conducted with some interviewees for additional insights and clarification.

Table 3: List of interview participants

Interview Participant ID	Institution/Stakeholder Group	Type of Interview
Interviewee 1	Waste management company 1	Video conferencing
Interviewee 2	Waste management company 1	Video conferencing
Interviewee 3	Waste management company 1	Video conferencing
Interviewee 4	Municipality	Email
Interviewee 5	Waste processing company 2 / Member of a waste management association	Video conferencing
Interviewee 6	Biodegradable plastics producer 3 / Member of a bioplastics association	Video conferencing
Interviewee 7	Research institute 4	Video conferencing
Interviewee 8	Research institute 4	Video conferencing
Interviewee 9	Plastics recycling company 5	Video conferencing

Themes

The questions within these data collection methods (survey and interviews) covered various themes: (1) *current roles and tasks*, (2) *levels of awareness and knowledge*, (3) *current practices*, (4) *barriers and challenges*, (5) *relations and collaborations with other actors*, (6) *suggestions for improvement* and (7) *support required by the various actors* (Adapted from Zacho et al., 2018).

The theme of *current roles and responsibilities* explores how different stakeholders are involved in the value chain of biodegradable plastics. Examining *levels of awareness and knowledge* involves determining resident awareness and knowledge of biodegradable plastics and their difference from other plastics, understanding of labelling, and knowledge of disposal practices. The theme of *current practices* explores the existing practices for handling biodegradable plastic waste, including resident sorting and disposal behaviours, and the technical processes involved in the collection, sorting and treatment of biodegradable plastics. Looking into *barriers and challenges* examines stakeholder concerns, organizational barriers and technical limitations. Exploring *relations and collaborations with other actors* involves exploring how various actors interact with each other, the communication channels and feedback mechanisms (if any) involved in the system. The theme of *suggestions for improvement* and *required support* involves gaining insights into stakeholder perspectives on system improvements, resources needed and infrastructure requirements.

These themes were adapted and re-designed to provide insights into the various components, interactions and aspects of the biodegradable plastic waste management socio-technical system, thus identifying its strengths, inefficiencies and opportunities for improvement.

The below Table 4 summarizes the data collection methods by stakeholder groups.

Table 4: Data collection by stakeholder group

Stakeholder Group	Data Collection Method	Rationale	Related to Research Sub-Question
Residents	Semi-structured surveys	To gain insights into resident awareness, knowledge and behaviours regarding biodegradable plastics; understand resident interactions with waste collection systems; identify challenges, barriers and rooms for improvement from their perspective	Sub-questions R1, R2, R3
Waste management companies	Semi-structured interviews	To understand the collection, sorting and treatment processes and technologies for biodegradable plastic waste; gain insights into challenges, barriers, infrastructure and resource requirements, and rooms for improvement; explore organization's attitude and perspectives on biodegradable plastics	Sub-questions R1, R2, R3
Municipality	Semi-structured interviews	To understand local regulations and policies around biodegradable plastic waste and its treatment; gain insight into their collaboration with waste management company	Sub-questions R1, R2, R3
Biodegradable plastics producers	Semi-structured interviews	To gain industry knowledge of biodegradable plastics, their standards and regulations; gain insight into labelling standards, disposal information and their perceptions of challenges in the waste management system	Gain more insight into the system

Waste management and biodegradable plastic industry associations	Semi-structured interviews	To understand the current state of biodegradable plastic waste treatment, its challenges and best practices; gain insights into industry perspectives on biodegradable plastics and broader industry trends	Gain more insight into the system
Researchers	Semi-structured interviews	To gain insight into the characteristics of biodegradable plastics, their advantages and limitations, their end-of-life options; gain insight into current research trends in biodegradable plastics	Gain more insight into the system

3.3 Data Analysis

The following section outlines the analysis methods used to analyze the quantitative and qualitative data gathered during the data collection phase. It then introduces a framework that builds upon the insights gained from these analyses to identify strategies for optimizing the biodegradable plastic waste management system.

Descriptive Analysis

The data collected through closed-ended survey questions was analyzed using descriptive statistics to gain insights into resident awareness, knowledge and disposal behaviours of biodegradable plastics. These insights consequently informed an understanding of the current biodegradable plastic waste management system, illuminating its strengths and inefficiencies from residents' perspective. This aided in answering research sub-questions R1, R2 and R3.

Descriptive statistics was used to summarize the data and understand respondent characteristics, as described by Simpson (2015). When summarizing categorical variables, the most straightforward method is reporting the proportion of participants in each category (Simpson, 2015). Thus, frequencies and percentages were calculated in this study to show the distribution of answers for each survey question.

These calculations were based on the number of complete responses. Any missing responses or inconsistent answers (eg. multiple answers for a single-answer question) were excluded from the calculations for each survey question. This approach was chosen over imputation because some survey questions only had a maximum of two to four missing or inconsistent responses (out of 412 participants). These responses account for less than 1% of the total dataset and can thus be considered trivial (Alam et. Al, 2023). The impact of missing data methods is trivial when the missing values are less than 1% (Young et al., 2011, as cited in Cheema, 2014). Therefore, excluding these responses was unlikely to significantly affect the findings. Additionally, imputation methods can introduced bias due to assumptions about the missing values.

The resulting findings are presented in the form of pie charts, bar graphs and tables to illustrate the distribution of responses across categories and enable visual comparison between different responses. Pie charts and bar graphs enable us to study the proportion of respondents within each category; bar graphs also illustrate absolute numbers (Simpson, 2015). Thus, these figures were selected for effective data presentation when deemed most suitable.

A limitation of the descriptive analysis approach is that the results cannot be generalized beyond the sample population. Nevertheless, descriptive analysis enables the identification of patterns and trends

within the sample population, thus providing valuable insights into resident perspectives of the biodegradable plastic waste management system.

Thematic Analysis

A thematic analysis was conducted for the data collected from the interviews and the open-ended survey questions. This analysis method provides a structured approach to analyzing qualitative data by identifying patterns or themes in the dataset and then interpreting their meanings; which can lead to new insights and understanding (Naeem et al., 2023). This study utilized a hybrid approach for the thematic analysis, guided by the pre-defined themes specified in the data collection section (Section 3.1) while remaining open to new themes emerging from the data. This approach combines the application of deductive and inductive thematic analysis to the same qualitative data, providing greater rigour to the study and combining the advantages of both methods (Fereday & Muir-Cochrane, 2006 as cited in Proudfoot, 2022). Using the hybrid approach facilitated a structured analysis with a focus on answering the research questions within the socio-technical systems (STS) framework, while allowing flexibility to discover new themes and insights without getting lost in the information.

Broadly following the well-recognized six-step process of thematic coding outlined by Braun & Clarke (2006), the thematic analysis involved transcription and familiarization with data, generation of initial codes, searching for themes, reviewing themes, defining themes, interpretation and synthesis (Proudfoot, 2022; Naeem et al., 2023). This six-step approach provides a “structured approach to coding and theme development”, while allowing flexibility in the thematic analysis (Xu & Zammit, 2020).

Interviews were transcribed verbatim and personal identifiers were pseudonymized before conducting analysis. The interview transcripts and open-ended survey responses were read and re-read in order to get immersed in the data. During the initial coding phase, the data was coded according to the pre-defined themes. When new codes emerged upon analyzing the data for patterns, these codes were incorporated into the analysis as well. This process integrated deductive and inductive coding; thus providing a balanced, comprehensive view of the data (Xu & Zammit, 2020). The codes were then grouped and refined into themes; a detailed overview of the coding structure with the generated codes and themes is provided in Appendix C. A limitation of thematic analysis is that it can inherently involve research bias due to its subjective nature. However, following a systematic, structured approach ensures thoroughness and can mitigate bias (Naeem et al., 2023).

By extracting themes and sub-themes from the data, the analysis aimed to identify recurring patterns in order to examine the social and technical sub-systems and the interactions between them, and capture stakeholder perspectives on waste management of biodegradable plastics and its potential optimization. This analysis revealed valuable insights into the existing strengths and inefficiencies in the current biodegradable plastic waste management system; thus aiding in addressing research sub-questions R1, R2 and R3.

Environmental Design Framework

This study utilized an environmental design framework taken from Kaplan et al. (2007) to identify potential strategies to optimize the biodegradable plastic waste management system in order to address the fourth sub-question (R4). This framework provides a structured approach to translate broad goals into concrete steps, and has been adapted to address the needs and challenges of the biodegradable plastic waste management system in Leeuwarden.

As indicated in Figure 3, the linear process of the framework involves four steps:

1. Experiences/domains of quality of life: This step involves identifying needs, goals and key domains of quality of life of the waste management system that are crucial for effective management of biodegradable plastics.
2. Design principles: This step focuses on translating the identified goals and domains into key desired characteristics or attributes of the biodegradable waste management system.
3. Design concepts: This step involves developing strategies within the physical and organizational environments of the biodegradable plastic waste management system to achieve the desired characteristics.
4. Design applications: The last step involves selecting and showcasing real-life examples or case studies that show how these strategies have been successfully or unsuccessfully implemented in the physical environment. These examples can inform future efforts to optimize the biodegradable plastic waste management system in Leeuwarden.

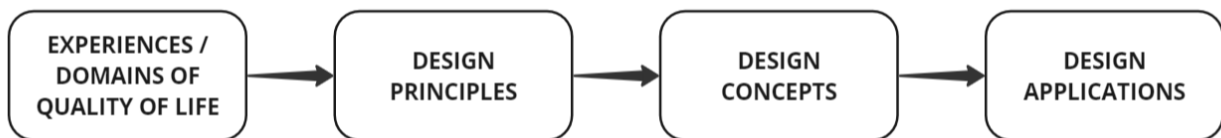


Figure 3: Steps outlining the Environmental Design Framework (Reproduced from Kaplan et al. (2007))

This framework provides a roadmap to move from identifying the needs of the system to providing practical solutions for implementation; thus highlighting the increasing specificity of the framework as an advantage (Kaplan et al., 2007). Effective implementation of this framework to identify optimization strategies requires a thorough understanding of the current system, its strengths and inefficiencies. The insights gained from analyzing the quantitative and qualitative data through descriptive statistics and thematic analysis, respectively, were crucial in informing the goals and needs of the waste management system necessary for effectively managing biodegradable plastic waste (Step 1 of the framework). This approach ensured that the strategies or solutions developed through the framework explicitly addressed the identified challenges of the biodegradable plastic waste management system in Leeuwarden.

3.4 Ethical Considerations

According to the research ethics policy of the University of Twente, all research projects conducted with human participants must be submitted for ethical assessment prior to starting the research. The request for ethical review was submitted via the BMS Ethical Review web application. The study was then approved by BMS Ethics Committee (EC) (University of Twente, n.d.) prior to the start of the research.

Survey participants were provided with an informed consent form detailing the objectives of the thesis, their right to voluntary participation and withdrawal at any time, and the use of the data for research purpose. They were informed that the collected data would be stored securely and deleted upon graduation. They were also assured that no personal identifiable data would be collected from them.

Interviewees' consent was obtained prior to recording the interviews. They were informed that their names and associated institutions would be pseudonymized to maintain confidentiality. This

pseudonymization was applied throughout the report and the interview transcripts. Additionally, any other potentially identifying details were removed or generalized. Anonymized interview transcripts with sensitive information paraphrased or redacted where necessary can be made available upon request, but only for those interviewees who provided explicit consent for this purpose. To ensure data security, the raw data containing names and personal identifiable information was stored securely using password protection and AES-256 encryption via Veracrypt. This raw, unprocessed data will be deleted upon graduation in September 2024.

4. Results

The results section presents the findings of the study, providing a detailed account of the current biodegradable plastic waste management system in Leeuwarden based on the data collected from both surveys and interviews. This section answers the first research sub-question (R1). A revised schematic diagram representing the current system in Leeuwarden is also provided.

4.1 Current Waste Management System (R1)

This section provides an overview of the current waste management system for biodegradable plastics in Leeuwarden, first focusing on the social sub-system and then the technical sub-system.

4.1.1 Social Sub-system

This section delves into the social aspects of the biodegradable plastic waste management system, covering key themes such as resident awareness and knowledge, resident behaviours, and interactions and collaborations between various stakeholders.

Resident Awareness and Knowledge

The survey results show that a majority of respondents (77%) were familiar with the term biodegradable plastics, indicating some level of awareness. However, 23% of these respondents either hadn't heard of biodegradable plastics or were unsure, suggesting there still exists a gap in general awareness.

The survey revealed confusion among respondents regarding differences between bio-based plastics, biodegradable plastics and bioplastics. Bio-based plastics are plastics made from renewable sources such as biomass or waste; bioplastics are plastics that are bio-based and/or biodegradable (Filiciotto & Rothenberg, 2021; Dilkes-Hoffman et al., 2019). Nearly half of the respondents (49%) correctly identified that bio-based and biodegradable plastics are not the same. However, a significant portion of them (44%) were unsure while 7% of respondents incorrectly believed that they were the same. In addition, 41% of respondents were unsure whether "bioplastics" and "biodegradable plastics" could be used interchangeably, while 21% believed they could be. Only 38% of these respondents correctly identified that these terms are not interchangeable. These findings show that there is a considerable misunderstanding among survey participants in regards to the terminologies of bio-based, biodegradable and bioplastics.

When it comes to perceptions about the biodegradation process, almost half of the respondents (49%) were unsure if biodegradable plastics break down completely under all conditions, while another 15% believed they always break down completely. These numbers highlight a significant knowledge gap around the biodegradation of these plastics and the conditions required for it.

The survey respondents expressed varying confidence levels in their ability to recognize biodegradable plastic labels. 36% of respondents expressed different degrees of confidence with 7% of these respondents responding 'very confident'. A significant portion (59%) expressed varying levels of uncertainty (refer to the table in Appendix A for a breakdown of confidence levels). Additionally, 5% revealed they didn't know how to identify these labels. This difficulty in identifying biodegradable plastics is further corroborated by a respondent who stated "I cannot recognize from the plastic whether it is a biodegradable plastic". Another respondent noted "Sometimes it's obvious, most times you really have to look".

The survey showed diverse responses among respondents when asked about their perception of the most suitable method for disposing biodegradable plastic waste as illustrated in Figure 4. A significant majority (43%) favoured a separate collection bin or collection point for biodegradable plastics while

35% opted for disposing in a bin or bag designated specifically for plastic waste. These numbers indicate a preference among the majority of respondents for a separate collection infrastructure for plastic waste. Furthermore, 38% of respondents selected disposal in organic waste bins as a suitable option. In contrast, smaller portions of respondents (20% and 21%) chose composting at home and disposing in the general waste bin, respectively. Lastly, the remaining 7% expressed that they didn't know the most appropriate disposal methods.

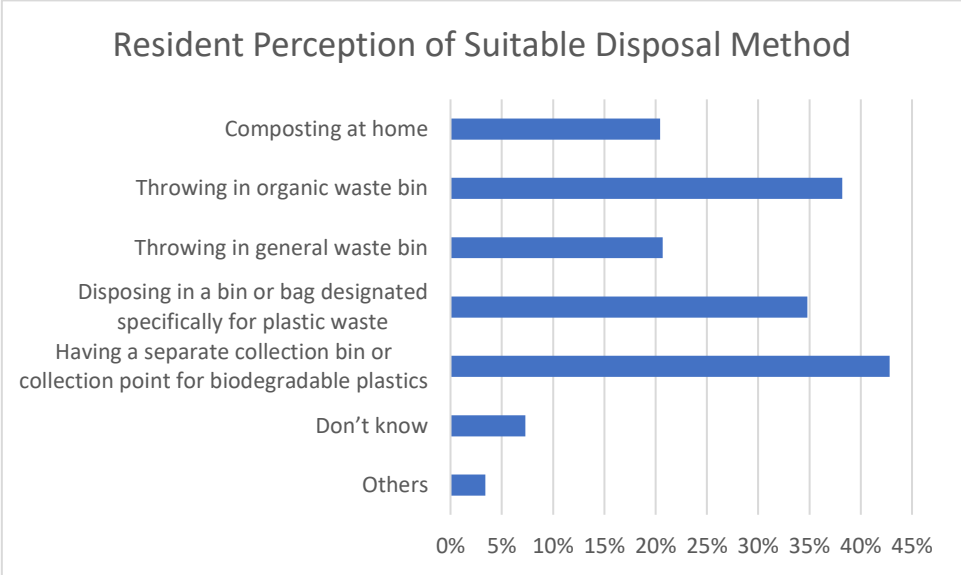


Figure 4: Resident perception of suitable disposal methods for biodegradable plastic waste

Some respondents provided additional insights; a few mentioned drop-off points or a central collection point to avoid having too many bins. Some noted that the waste processing company handles waste separation afterwards. A few others mentioned that the disposal method varies; one respondent emphasized that “it depends on the decomposition time”. Furthermore, a respondent mentioned that biodegradable plastics do not seem to decompose in GFT (organic waste). These varied responses highlight the diverse opinions and perceptions among survey participants regarding the most suitable methods for disposing biodegradable plastic waste.

Additionally, the survey asked respondents how important they think it is to have separate collection systems for biodegradable plastic waste. A significant majority (72%) indicated that separate collection points were important or very important. It is important to note that this question may have been leading, potentially influencing respondents to select separate collection points. However, this finding aligns with the preference for separate collection point for biodegradable plastic waste as observed in the responses to the previous question.

Interestingly, a respondent commented “I don't have much knowledge about what materials they are made of, how long it takes for them to be composted or whether current waste disposal processes can remove them”. This reflects the gaps in knowledge regarding the composition, biodegradation and disposal of biodegradable plastics identified in the survey findings.

Resident Behaviours

When it comes to general household waste separation practices among survey respondents, the results revealed that a significant majority (75%) currently separated their household waste into separate bins. However, a considerable gap in waste separation still exists; with 25% of respondents either not

separating their waste (5%), only doing so sometimes (15%) and having lack of access to separate bins (5%).

When respondents were asked about the frequency with which they purchased products and/or packaging with biodegradable plastics, half the respondents (50%) reported sometimes, while 13% stated they do so often. However, a significant portion of respondents (30%) expressed uncertainty about the frequency, stating that they didn't know. The purchasing frequency of respondents is illustrated in Figure 5.

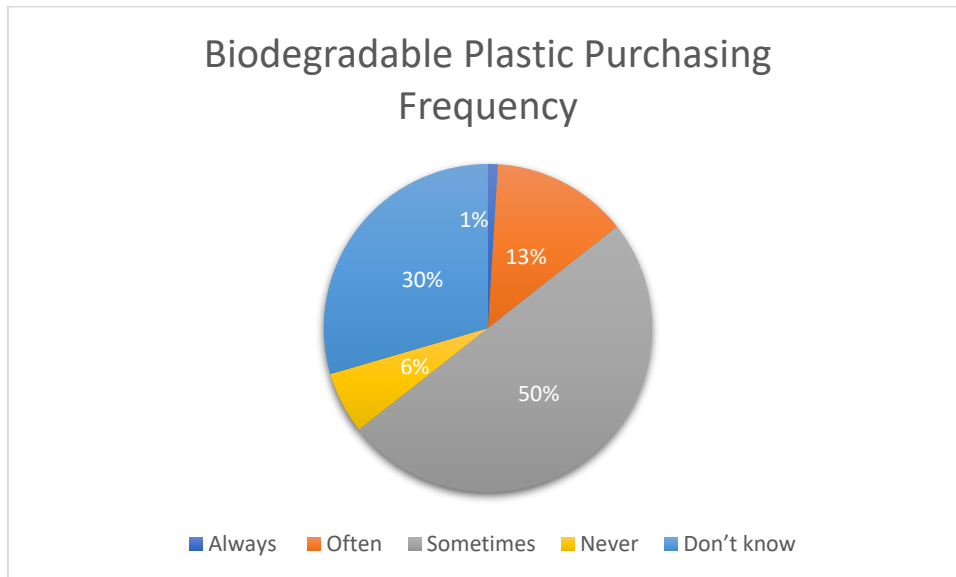


Figure 5: Frequency of purchasing biodegradable plastic products/packaging

When the respondents who purchased products and/or packaging with biodegradable plastic were asked where they disposed the biodegradable plastic waste, 53% reported that they disposed them in the general waste bin and 33% indicated disposal in the organic waste bin as depicted in Figure 6. Another 5% disposed them by composting at home. 13% of respondents reported disposing in a bin or bag designated specifically for plastic waste. However, according to the waste management company, there is no such separate bin available specifically for household plastic waste.

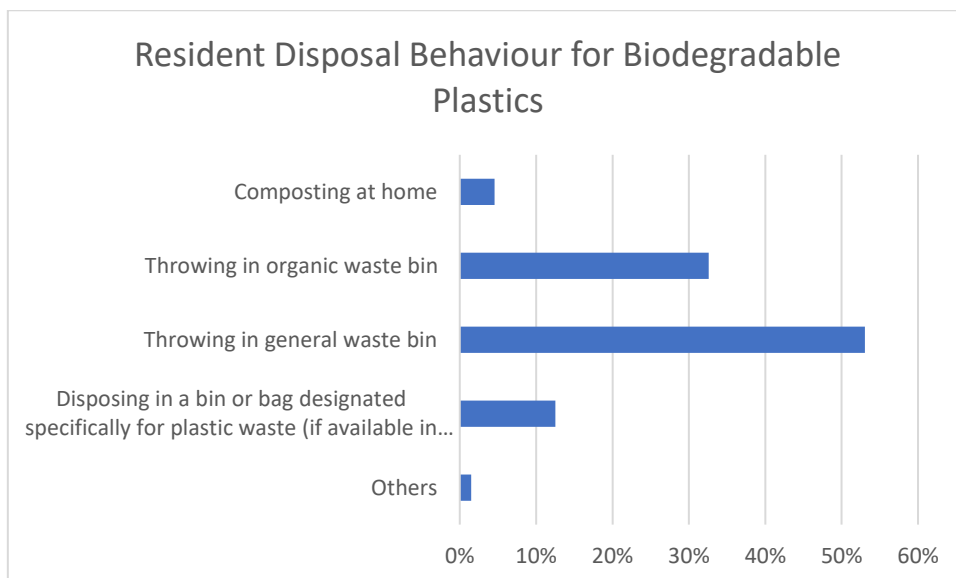


Figure 6: Resident disposal behaviour of biodegradable plastic waste

These diverse disposal behaviours highlight the complexity in waste management of biodegradable plastics. Interviews from waste sector professionals further highlight this complexity. The findings from interviews indicate that biodegradable plastic waste is largely recommended to be disposed in the residual waste bin. One interviewee specified “It is advised to do it in a residual bin”. The email interview with a municipality representative indicated that biodegradable plastics should not be disposed in the green bin; “the problem is that it would take too long for the biodegradable plastics to be graded down. The regular fraction of the green bin grades down much faster.” Only a few specific biodegradable products are suitable for the organic waste bin. The municipality representative mentioned that currently only biodegradable plastic waste bags are allowed in the organic waste bin. Furthermore, a waste management personnel elaborated that only compostable waste bags, tea bags, coffee capsules and food stickers belong in the organic waste bin.

Interactions and Collaboration Between Stakeholders

The survey demonstrated that a significant majority of respondents receive waste disposal updates from the waste management company through various channels and mechanism such as app notifications, information letters and social media. Additionally, survey respondents also mentioned they get disposal information through the waste calendar, weekly newspaper, word of mouth, etc. This indicates a strong level of engagement between residents and the waste management company.

However, when asked about ways that they can provide feedback to the waste management company, a significant majority of respondents (78%) indicated that they didn’t know how to provide feedback. This finding signifies a major gap in resident knowledge about feedback mechanisms and a potentially large communication gap between residents and the waste management company. Only 22% of respondents noted that they knew how to give feedback. Some of these respondents mentioned providing feedback using the app, social media, the waste management company’s contact form or contact details, etc.

An interview from a waste management company personnel (Interview 1) provided additional insights on the available feedback mechanisms. The interviewee explained that they get questions or remarks from the public through their various channels including a service number where people call at the office for any enquiries or feedback. The interviewee further elaborated that while the amount of feedback is not large, they do take resident feedback into consideration, as highlighted by the statement “It’s not so much that we get but of course the remarks we get, we try to do something with it.....to have critical followers it’s always good.” These survey and interview findings suggest that while there are various feedback channels available and the waste management company may be open to receiving and addressing resident feedback, a significant portion of residents may not be aware of these feedback mechanisms; thus hindering the city’s waste management company’s ability to gather valuable resident perspective and consequently improve the waste management system.

While not targeted specifically for biodegradable plastic waste, the waste management company together with the shareholding municipality holds public awareness campaigns to positively influence resident disposal behaviours. They utilize a combination of online and offline strategies in public spaces and through digital platforms, respectively, to increase awareness and educate about proper disposal practices. The waste management company tracks critical KPIs (details confidential) to measure their effectiveness of their public awareness and education campaigns. They also conduct sorting tests to measure the impact of these campaigns, as confirmed through an email interview with a municipality representative. The municipality also gathers feedback from residents through neighbourhood interviews and surveys; after which the results are summarized and considered for incorporation. These initiatives demonstrate active efforts at engaging with residents to influence behaviour.

Thus, the social sub-system reveals gaps in respondents' knowledge about biodegradable plastics and varying disposal behaviours. Despite public awareness campaigns and availability of feedback mechanisms, a notable communication gap exists between residents and waste authorities.

4.1.2 Technical Sub-System

Waste Stream

The waste stream of biodegradable plastics in Leeuwarden is relatively small. This is corroborated by the interviewed personnel from the waste management company. One interviewee (Interviewee 2) stated "It's a very small stream, the amount of biodegradable plastics that is in the waste now". This minimal volume poses a challenge in integrating biodegradable plastics into the existing waste management system.

Collection Infrastructure

In terms of waste collection infrastructure, residents in Leeuwarden are provided the organic waste bin, the general/residual waste bin and paper waste bin for waste separation. Interviews with waste management personnel confirm that there is no separate collection bin or collection point for plastic waste including biodegradable plastic waste. Plastic waste is collected in the general or residual waste bin together with other household waste (except organic waste and paper); and then separated after collection in the sorting phase.

Sorting Technologies and Processes

Currently, biodegradable plastic waste collected in the residual bin is not sorted due to its very minimal volume. Interviewee 3 from the waste management company stated "In our sorting plants, we can only pursue maybe 10 steps. So we can sort 10 sorts of waste. And what we do is that we sort those 10 wastes, which are biggest in volume". This indicates that the sorting infrastructure is designed to prioritize segregation of waste types that occur in large volumes. The interviewee explained that while new technologies and new techniques are not needed to sort biodegradable plastics, the current volume is too small to justify adding this step into the sorting process. He further elaborated "If the biodegradable waste is too little in volume, we don't separate it because it makes no sense." Interviewee 9 from the plastic recycling company adds that "it doesn't make any sense to put additional equipment and reserve additional space in the plastic sorting facilities to make a separate fraction out of it", considering the small fraction of biodegradable plastic waste in the current waste streams. He further explained that additional space would be required for the plastic sorting equipment, conveyor belts and the separate bunker or container to hold the sorted plastic, which is not justifiable for such a small fraction. These viewpoints reinforce the argument from the waste sector that the current minimal volume of biodegradable plastic waste does not warrant investments in sorting infrastructure.

Treatment Processes

For the biodegradable plastic waste that occurs in the organic waste bin, the compost is sieved at 12 to 15 millimetres. Due to the relatively long time required for biodegradable plastics to degrade, the plastics remain above the sieve. Interviewees from the waste sector explained that organic waste in composting plants take three to six weeks to form compost; however, biodegradable plastics don't compost in that time. Consequently, these biodegradable plastics that remain above the sieve are sieved off and then "everything from there goes into the incinerators". Ultimately these plastics are burnt and converted into heat and electricity. Thus, there is no composting of biodegradable plastic waste currently in practice as "it takes too much time to make compost from it", Interviewee 2 explains.

As for the biodegradable plastic waste in the residual bins, during the sorting process for plastics, these biodegradable plastics are sieved off and added to the non-recoverable residual waste, which is then incinerated. Currently there is no option for recycling biodegradable plastics. Interviewee 3 further expanded “We always ask ourselves if we want to recycle the product, where do we bring it?”

Thus, the technical infrastructure is not currently designed for efficient management of biodegradable plastic waste considering its limited volume, leaving most biodegradable plastics to be incinerated rather than composted or recycled.

4.1.3 Broader Context

At a broader level, while there is a focus on reduction of residual waste, there are currently no local regulations or policies specifically addressing biodegradable plastic waste in Leeuwarden, as confirmed by the municipality representative. The Netherlands has a National Waste Plan with a Yes/No list where biodegradable plastic packaging is not allowed in the organic bin; only certain products are allowed in this list. This was corroborated by email correspondence with a Dutch government agency representative.

4.2 Summary at the Socio-Technical Systems (STS) Level

A majority of respondents actively participate in waste separation, demonstrating the effectiveness of the current waste collection infrastructure in influencing residential sorting behaviour. However, there exists significant gaps in knowledge and varying disposal behaviours among respondents. Misconceptions around terminology and confusion regarding degradation properties and appropriate disposal methods of biodegradable plastics exists. Despite people’s best efforts to segregate waste, these knowledge gaps can result in improper disposal practices, leading to unintentional contamination of waste streams at sorting facilities. While there exists public awareness campaigns launched as collaborative efforts between the waste management company and the municipality to influence resident behaviour, these initiatives are not specifically targeted for biodegradable plastics. Furthermore, there is a notable gap in communication and awareness of feedback mechanisms between residents and waste management authorities. The current technical infrastructure prioritizes high volume waste streams, and the minimal volume of biodegradable plastic waste does not justify investments in dedicated sorting infrastructure or additional space in sorting facilities. Consequently, these plastics are sieved off from organic compost as well as the plastic waste stream, and then incinerated. This likely suggests a misalignment between consumer expectations and actual practice for the disposal of biodegradable plastic waste. The interplay between the social and technical components can significantly influence the overall effectiveness of the biodegradable plastic waste management system, which highlights the need for a holistic approach to addressing challenges within the system.

4.3 Schematic Diagram of the Current System

The following Figure 7 represents the revised schematic diagram of the current biodegradable plastic waste management system in Leeuwarden, as identified through survey responses and interviews. The solid lines represent existing processes or flows while the dotted lines indicate missing elements or future options that are currently not in place but can be implemented in the future.

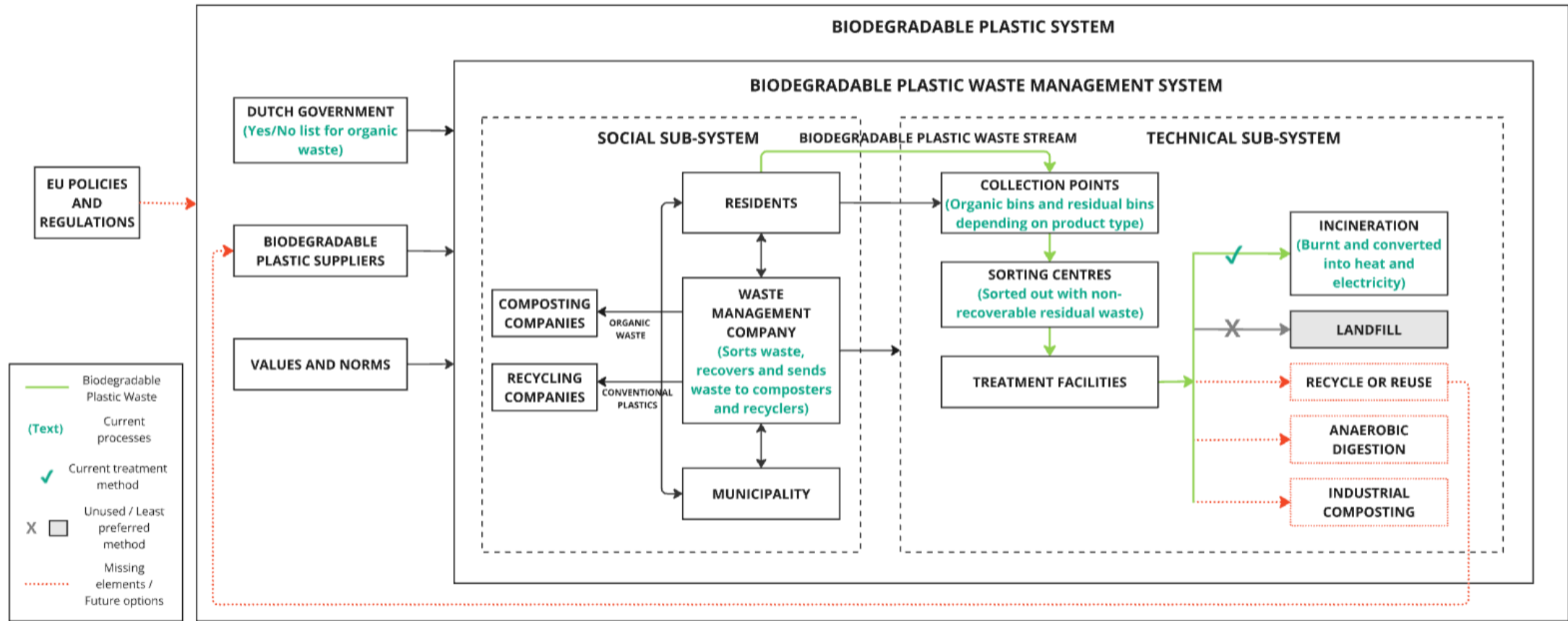


Figure 7: Revised schematic diagram of current biodegradable plastic waste management system in Leeuwarden with its social and technical sub-systems (Source: Author)

5. Discussion

This section examines the strengths and inefficiencies of the current biodegradable plastic waste management system in Leeuwarden. Based on insights from survey responses and interviews (as described in Section 4), and relevant literature (Section 2 and additional sources), this section delves into both the positive aspects and the areas needing improvement. The discussion section further explores strategies for transitioning the current system into a more optimal system. In doing so, this section answers the research sub-questions R2, R3 and R4 (The research sub-questions R1 was addressed in Section 4). Interweaved throughout this section will be interactions and interplay between the social and technical aspects of the system and their mutual influence on each other.

5.1 Strengths of the Current System (R2)

Building on the results section, this section examines the strengths of the current biodegradable plastic waste system in Leeuwarden. It delves into aspects of the current system that contribute to its effectiveness and highlights areas that can be built upon to effectively integrate biodegradable plastics into the existing waste management system.

The survey findings revealed a general awareness of biodegradable plastics among respondents with many demonstrating some level of understanding regarding the difference between bio-based plastics and biodegradable plastics. A notable segment of respondents also recognized that bioplastics and biodegradable plastics are not interchangeable; thus demonstrating a basic understanding of these terminologies. This awareness is crucial in accurately identifying plastic types and thus avoiding improper waste disposal practices. These findings can serve as a baseline foundation for resident education and increasing public awareness and knowledge about biodegradable plastics.

A significant majority of respondents participated in separation of household waste in general, indicating a strong engagement with the existing waste collection infrastructure. Additionally, according to Interviewee 3, the company together with the municipality has introduced a DIFTAR i.e. a differentiated tariff/pricing system to encourage residents to reduce and sort their waste. This highlights that collection infrastructure and financial schemes influence more efficient waste separation behaviour among residents. This aligns with literature where studies have identified tools such as convenient waste collection system at home, increased tariffs (when waste is not separated properly) and financial incentives like reduced tariffs having an influence on sorting behaviour (Minelgaitė & Liobikienė, 2019). This demonstrates that the technical sub-system can positively influence the social sub-system and thus highlights the importance of designing waste management systems to encourage desired resident behaviour.

The waste management company and the municipality collaborates on public awareness campaigns aimed at educating residents and improving sorting behaviour. These campaigns utilize various online and off strategies such as social media campaigns with influencers and animations, guerilla marketing and the provision of waste coaches at public spaces and events. Furthermore, the waste management company utilizes multiple communication channels to keep residents informed about waste disposal updates. These efforts show a proactive approach to resident engagement and education; aligning with the idea that information or knowledge through campaigns and prompts being effective tools for promoting sorting and disposal behaviours (Minelgaitė & Liobikienė, 2019). While not specifically targeted for biodegradable plastic waste, these educational campaigns can serve as starting points for developing initiatives to improve understanding and proper disposal behaviour of biodegradable plastics. Both the DIFTAR system and the awareness campaigns highlight the dynamic interactions and bidirectional influence between the social and technical components within a socio-technical system;

where insufficient or inefficient waste sorting and disposal behaviour of residents drive technical interventions which have a regulating influence on the social system (resident behaviour).

Additionally, resident behaviour can drive the adaptation and evolution of technical systems. This is illustrated by the example of tea bags in the Netherlands, for which various interviewees 5, 6 and 8 each provided their insights. Until some years ago, a large majority of consumers were disposing traditional tea bags in the organic waste, not knowing that they contained plastic, more specifically non-compostable polyethylene; thus contaminating the organic waste stream. In response to this emergent problem, the Green Deal was established between tea bag and coffee pad producers and the Dutch government at the initiative of an advocacy organization for the tea and coffee sector in collaboration with various companies and a Dutch waste association, where the producers were required to make these products compostable. This was highlighted by Interviewee 4, who added that the producers changed the polyethylene for polylactic acid (PLA) (a biodegradable plastic type). Consequently, all tea bags and coffee pads in the Netherlands are now compostable. Interviewee 8 emphasizes the importance of this step.

This case demonstrates the adaptive capacity of complex systems to evolve over time in response to challenges. This response can be seen as a balancing feedback loop; whereby undesired consumer behaviour triggered a corrective action, prompting stakeholder collaboration across the value chain leading to policy changes and consequently changes in product design. This case illustrates how the system evolved in response to consumer behaviour through dynamic interactions between the various social actors and technical components of the complex system. Furthermore, it highlights the system's capacity for self-organization as showcased by the industry-driven initiative to address the issue of plastic tea bags ending in organic waste. While the involvement of the government was necessary, the drive for corrective action came from the industry itself and their debates with the waste sector.

The waste management company has a successful waste recovery rate of 78% for various recyclable and recoverable waste including various conventional plastics. While biodegradable plastics are currently not recycled or composted which are higher order priorities in the EU waste hierarchy (Liu et al., 2023; European Union, n.d.-b), these plastics are incinerated and converted into heat and electricity. Incineration provides a better alternative than disposal in landfills since it recovers energy and also prevents the accumulation of these plastics in landfills.

The current system in Leeuwarden exhibits various strengths such as a basic foundation of public awareness, resident engagement with current collection infrastructure and active waste separation, resident education initiatives, established communication channels and efficient energy recovery through incineration. These strengths can be leveraged when implementing optimization strategies to integrate biodegradable plastics into the existing waste management system more effectively.

5.2 Inefficiencies of the Current System (R3)

This section explores the inefficiencies of the current biodegradable plastic waste system from the perspectives of the various actors involved in the value chain. Given that biodegradable plastics are a relatively small and new waste stream, several inefficiencies and challenges have been identified; which are crucial to address in order to optimize the system.

Knowledge gaps and consumer confusion

While the survey indicated general awareness of biodegradable plastics among survey respondents, it highlighted significant gaps in public awareness and knowledge. Nearly a quarter of respondents had not heard of biodegradable plastics or were uncertain they had, indicating there is a segment of respondents that lacked a baseline level of awareness. Notably, the survey observed inadequate knowledge regarding the biodegradation of these plastics among a substantial proportion of

respondents (66%). Furthermore, a vast majority either expressed uncertainty or incorrectly distinguished between bio-based vs. biodegradable plastics vs. bioplastics vs. biodegradable plastics.

Several studies (Zwicker et al., 2021; Paul-Pont et al., 2023; Fletcher et al., 2024) support these survey results, noting that consumers often confuse and misinterpret the terms ‘bioplastic’, ‘bio-based’ and ‘biodegradable’ plastics; and are unable to distinguish these terms, mistakenly believing they can be used interchangeably. These studies highlight that consumers often believe that bio-based plastics are inherently biodegradable when in reality, bio-based plastics can be both biodegradable and non-biodegradable. Furthermore, there are both bio-based and fossil fuel-based biodegradable plastics (Filiciotto & Rothenberg, 2021; Fletcher et al., 2024). The differences between these terms are illustrated in Figure 8.

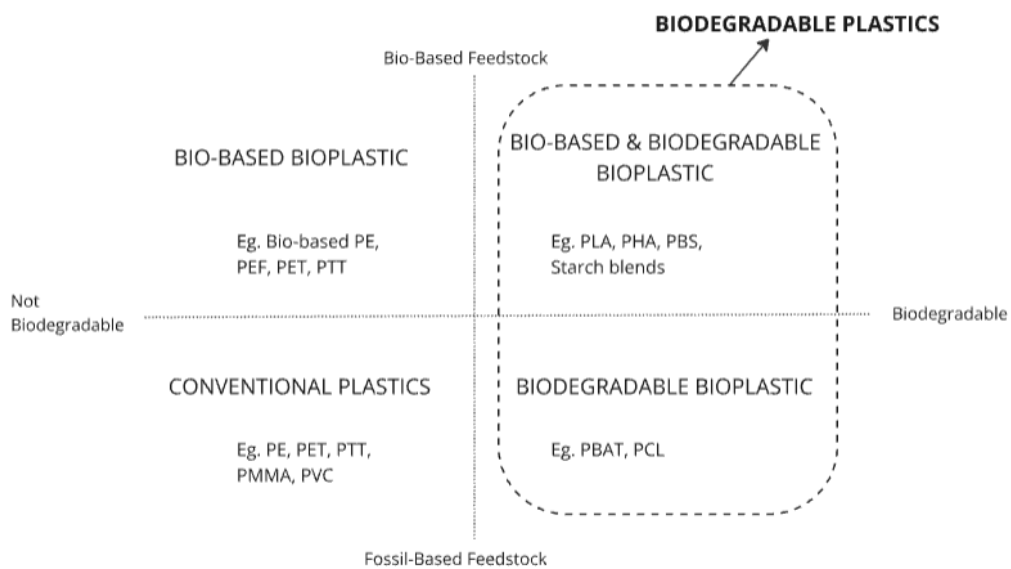


Figure 8: Bioplastics vs bio-based plastics vs biodegradable plastics (Adapted from European Bioplastics, n.d.-a)

Interviewee 6 from the biodegradable plastics industry noted that such confusion over terms is not uncommon, stating that people often have similar confusion when distinguishing different kinds of paper products. This demonstrates that this confusion over terminologies is part of a broader challenge of consumer misconceptions across different product categories. However, considering that this confusion pertains to plastic, it is crucial not to underestimate the impact of this issue. The misunderstandings over these terminologies can lead to improper disposal practices, which can pose challenges for waste management systems and the environment.

To add to the confusion, comments from some survey respondents expressed difficulty in recognizing biodegradable plastics; which are nearly identical to conventional plastics (Dilkes-Hoffman et al., 2019 as cited in Findrik & Meixner, 2023). This confusion is further corroborated by multiple interviewees. Interviewee 6 stated “For consumers, all packaging is packaging”. Both Interviewees 2, 5 and 9 from the waste sector explained that people cannot see the difference between biodegradable and fossil-based plastics.

These findings indicate significant knowledge gaps regarding biodegradable plastics and resident confusion around terminology, thus potentially leading to improper disposal practices and inefficiencies in the biodegradable plastic waste management system. As highlighted by Allison et al., 2021, a lack of awareness and knowledge regarding biodegradable plastics can lead people to engage

in incorrect waste disposal behaviors. This points to a systemic issue in public understanding of biodegradable plastics, which can impact the efficiency of the technical waste management system, especially if the volume of these plastics grows in the coming years.

The implications of this systemic issue is further highlighted through stakeholder insights. Interviewee 2 stated that biodegradable plastics are causing more confusion among consumers, leading to an increased presence of plastics in compost. Both Interviewee 5 and Interviewee 7 (from the research institute) highlight the increasing risk faced by composters of non-biodegradable or non-compostable plastics entering their system. This illustrates a clear feedback loop where a product intended to improve plastic waste management unintentionally reinforces improper disposal and management of plastics.

Additionally, the survey revealed varied levels of uncertainty among a substantial majority of respondents regarding their ability to recognize biodegradable plastic labels. Studies such as Zhu & Wang, 2020 and Fletcher et al., 2024 highlight that labels are an additional source of consumer confusion. A lack of a harmonized labelling system makes it challenging for consumers to identify biodegradable plastics (Findrik & Meixner, 2023). These complexities in terminology and labelling lead to misconceptions among consumers that can hinder proper disposal and waste management practices. This emphasizes the need for clear and standardized labelling and consumer education efforts, which can help address these challenges and improve consumer separation and disposal practices.

However, even with clearer labelling enabling identification of biodegradable plastics, the lack of knowledge regarding the differences between these terms can still persist and cause confusion among consumers. While it is essential to educate consumers and residents on these terminologies, it's important to recognize the complexities of bioplastics and biodegradable plastics as depicted in Figure 8. Thus, the entire burden of responsibility shouldn't be placed on consumers. Instead, it is crucial to have clear disposal information or guidelines for these plastics.

Several interviewees from the waste sector and biodegradable plastic industry including researchers emphasized the importance of providing specific disposal instructions on biodegradable products. Interviewee 5 explained that the labels themselves have no meaning; instead, the packaging should include clear information on which bin to dispose them. Interviewee 6 stressed that it should be mandatory to specify bio-based content, more specifically the bio-based content in percentages and also its end-of-life option. In contrast, interviewee 8 stated "The consumer doesn't need to know. They don't care whether it's polypropylene or polylactic acid. As long as they know, I can put this in the right bin without problem and actually with a benefit". This highlights a general consensus among several interviewees on the need for clear disposal information on biodegradable products and packaging, though there are differing opinions on the level of detail required.

Labels with clear disposal instructions can serve as a critical interface between the technical system (product) and the social system (consumer behaviour). By providing clear and accurate information, labels can significantly reduce consumer confusion and influence their disposal practices, consequently improving the efficiency of the waste management system. This interplay between clear labelling, consumer understanding and waste management practices can be seen as a balancing loop. Effective labels can facilitate proper disposal behaviours, reducing contamination and optimizing waste processing, thus helping to regulate the system.

Resident perceptions and practices

A notable proportion of respondents (51%) purchase and use biodegradable plastic products or those with biodegradable plastic packaging, suggesting some level of demand in the market. However, the

fact that only a small percentage of respondents (7%) use these products frequently indicates that the use of biodegradable plastics is currently not widespread. The cost of these plastics is considerably higher than conventional plastics, thus limiting their penetration in the market (Pahlevi & Suhartanto, 2020 as cited by Soareas et al, 2020). Furthermore, as a significant portion of respondents (28%) expressed uncertainty regarding their purchasing frequency, this might indicate that biodegradable plastics are not a consideration in their purchasing decisions or it might be indicative of their inability to recognize these plastics.

A systematic review conducted by Findrik & Meixner (2023) highlight that the main purchasing barriers for bioplastics are consumers' lack of knowledge, uncertainty about recognition and ambivalent feelings towards these plastics. This emphasized the role that knowledge of these plastics play in influencing purchasing decisions. Additionally, building consumers' knowledge about bioplastics positively influences their willingness to pay for these products (Findrik & Meixner, 2023). In addition to the functional features of these plastics, informing consumers about their environments may also influence purchasing choice and willingness to pay. These insights can be extrapolated to biodegradable plastics and highlights how consumer education efforts and standardized labelling can not only influence disposal behaviour but also have the potential to drive market demand.

The survey findings in Section 4 revealed that respondents have different perceptions regarding proper disposal practices for biodegradable plastic waste. Studies such as Findrik & Meixner (2023), Fletcher et al. (2024) and Allison et al. (2021) noted that consumers have a limited or a lack of knowledge regarding disposal of these plastics. This is further corroborated by majority of the interviewees, who reported that consumers often experience confusion over which bin to dispose biodegradable plastics. Thus, these varying perceptions of suitable disposal methods can potentially lead to improper disposal practices, resulting in inefficiencies in the waste management system.

Responses to multiple survey questions indicate a preference for separate collection infrastructure for biodegradable plastics. Comments from some respondents reported the inability to separate waste as one of the challenges in the current system, and requested more options for separation including a separate plastic bin. These findings hint at respondents' preference for separate collection of plastics in general, not necessarily for biodegradable plastics. This indicates a significant disconnect between respondent preferences and current collection infrastructure, where plastics are collected in the residual bin. While some respondents expressed a desire for dedicated collection infrastructure, a few others emphasized simplification. One respondent suggested making the collection process as straight forward as possible.

Given that collection infrastructure can influence resident sorting behaviour as specified in Section 5.1, the lack of separate collection bins or designated points for plastics and the disposal of plastics together with general household waste (except organics and paper) can impact how residents perceive waste management practices. It can potentially cause residents to have a less mindful attitude towards waste sorting and recycling efforts in general, thus hindering effective waste management. According to Knickmeyer (2020), pre-sorting of household waste streams at source is essential for improving recycling performance, maximizing resource recovery and reducing contamination in recycling streams. A primary concern of the municipality in Leeuwarden is the reduction of residual waste. While the waste management company achieves a successful 78% waste recovery rate with the current infrastructure, the lack of options for separation can result in a reduced sense of responsibility among residents, with them assuming that waste separation will be handled by the waste management company. This can consequently undermine the municipality's goal of reducing residual waste.

In terms of actual behaviour, over half of the respondents who purchased products and/or packaging with biodegradable plastics disposed this plastic waste in the general/residual waste bin, while 33% mentioned disposing in the organic bin. Interviews with the waste management company and the municipality revealed that it is advised that biodegradable plastic waste be discarded in the residual waste bin, with only certain biodegradable plastic products (like organic waste bags, tea bags, etc.) being allowed in the organic bin. The fact that different products and/or packaging with biodegradable plastic have different recommended disposal methods highlights the complexity in the waste management of these plastics, leading to unintended consequences within this complex system. To illustrate this point, Interviewee 2 stated that biodegradable plastics can cause confusion among people who are doing their best to separate waste, elaborating “So if you say one kind of capsule can be disposed at the green bin and another one is not, it might confuse the consumer.” Such confusion results in more and more plastic being found in the bio bin. This further emphasizes the complexities that come with the disposal of these plastics, and reinforces the need to properly educate residents and provide clear disposal information.

It is important to note that 20% respondents view composting at home as a viable method for disposing biodegradable plastics (though only a small percentage of respondents reported actually composting these plastics at home). Fletcher et al. (2024) and Paul-Pont et al. (2023) highlighted that consumers often misinterpret the terms compostable and biodegradable; not all biodegradable plastics are compostable. According to Zhu & Wang (2020), a drawback around the term ‘biodegradable’ is that it doesn’t contain any details about “the location, time scale and extent of the decomposition process”. Several studies (Mut et al., 2024; Afshar et al., 2024; Liao & Chen, 2021) indicate that biodegradable plastics degrade under specific environment conditions. While the survey does not indicate whether people compost non-compostable biodegradable plastics, the significant lack of knowledge regarding the biodegradation of these plastics among a majority of respondents (63%) is concerning as it can lead to unintended consequences such as improper disposal especially among residents who may mistakenly believe that all biodegradable plastics are compostable; further emphasizing the need for disposal information on labels.

Further complicating this issue, Interviewee 8 provided deeper insights into the challenges of home composting, explaining that while there are many products that can be composted at home, he doesn’t see home composting as a suitable end-of-life option for man-made home compostable products which require specific conditions like nutrient composition, aeration, etc. He elaborates “If you move this waste treatment to the people at home, you get a lot of uncontrolled waste treatment”. He added that this can also result in unwanted emissions, and emphasized the need for centralization.

These cases illustrate the interplay between social and technical aspects within the waste management system. Different product types and their associated disposal requirements influence consumer behaviour, which in turn has an impact on the waste management system or the ecological environment depending on the disposal behaviour. They also highlight that how complexities within the system can result in unintended consequences in other parts of the system; emphasizing the significance of consumer education and clear labels to avoid such unintended consequences.

These concerns identified thus far are further corroborated through survey results when respondents were asked about the challenges that residents in Leeuwarden face in disposing biodegradable plastic waste properly. As illustrated in Figure 9, the major challenges that respondents reported were a lack of easily accessible collection bins or collection points, lack of clear disposal information on the packaging and difficulty identifying biodegradable plastic due to unclear labelling. Additionally, a considerable proportion of respondents highlighted low communications efforts from the waste management company about proper disposal of biodegradable plastics. While there are public

awareness campaigns carried out by the waste management company in collaboration with the municipality, interviews with representatives from both stakeholder groups confirm that there are currently no educational campaigns targeted specifically for biodegradable plastic waste, considering it's a relatively small waste stream. However, as the production of these plastics and subsequent waste stream continue to grow, it will be increasingly crucial to address these communication gaps.

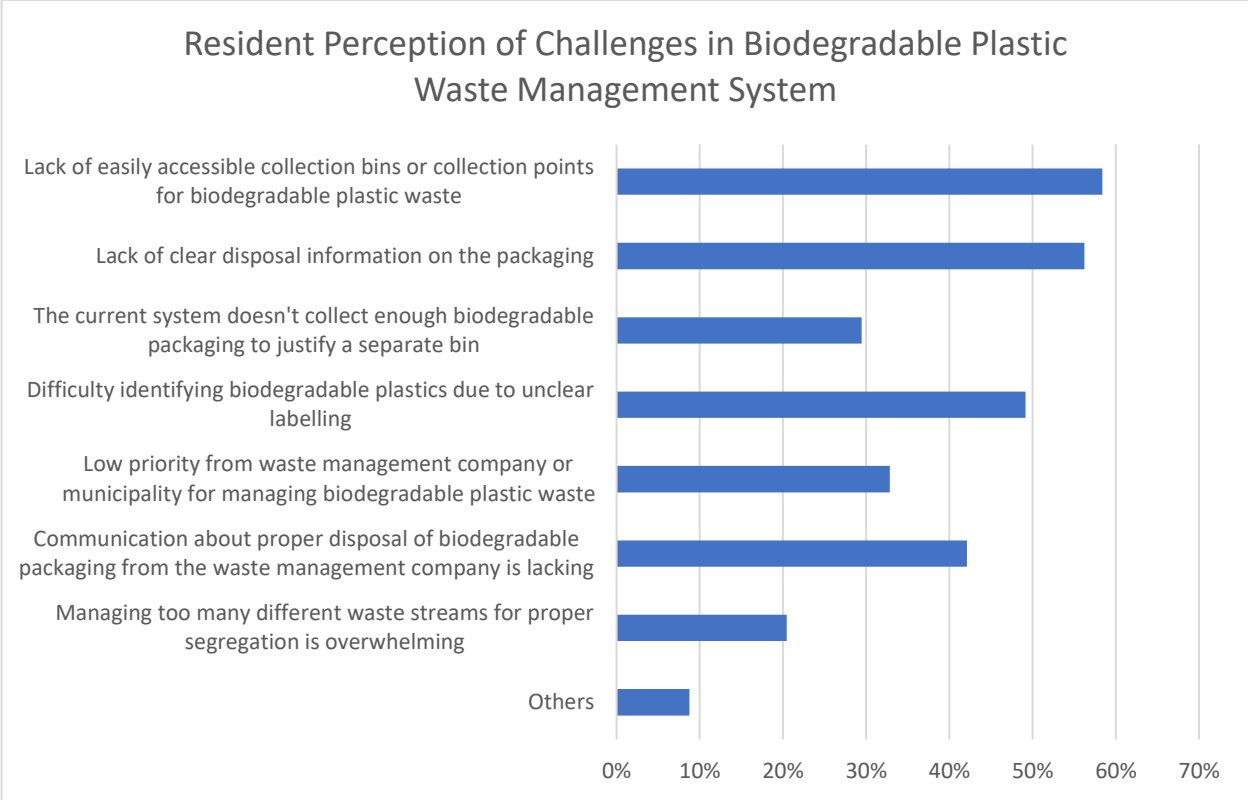


Figure 9: Resident perception of challenges in biodegradable plastic waste management in Leeuwarden

Technical Constraints

Insights from representatives of the waste management company revealed that the waste stream of biodegradable plastics is relatively very small. This can likely be attributed to the limited availability of biodegradable plastic products or packaging in the market, as one survey respondent noted that there was “not enough packaging in stores that is made from biodegradable plastics”. Additionally, this small volume is likely due to the lack of widespread use of these plastics among respondents as discussed earlier. This illustrates how the interplay between market demand influenced by product availability and consumer preferences and subsequent purchasing behaviour affects the volume and composition of waste streams. These dynamic interactions highlight the influence of social factors (such as consumer behaviour and market dynamics) on the technical waste management system.

When it comes to managing biodegradable plastic waste, Interviewee 2 from the waste management company acknowledged the advantage of biodegradable plastics being plant-based but emphasized that “in waste treatment and recycling, it has no advantage. You cannot close the loop for that at the moment”. Due to the small volume of the biodegradable plastic waste stream, these plastics found in the residual waste bin are currently not sorted. Interviewee 3 elaborated that the percentage of biodegradable plastics in the total plastic volume is so small that it doesn't pay to incorporate this step

into the sorting infrastructure, as the biggest fractions of plastics are prioritized. Several interviewees from both the waste and biodegradable plastics sectors mentioned that it is technically possible to sort biodegradable plastics. Interviewee 3 added there is no need for new sorting technologies and techniques; however, the small waste stream does not justify investing into additional space with sorting infrastructure and equipment, as highlighted by Interviewee 9.

Interviewee 5 further explained that sorting of biodegradable plastics such as polylactic acid (PLA) only becomes economically feasible when the volume of these plastics reach a certain threshold. He stated “When you have enough PLA, then we can sort it out. But the problem now is that there is a small amount of PLA in the plastic waste. So, it is not interesting to sort them out”. When the volume of PLA becomes more than 5 or 10%, then there is more of an incentive to sort it separately. Additionally, he emphasized the role of financial incentives in making sorting of biodegradable plastics feasible. In the Netherlands, producers are required to pay for sorting, making sorting of these plastics economically attractive provided that there is sufficient volume of PLA.

Interviewees 7 and 8 provided interesting insights, highlighting the chicken and egg dilemma in sorting biodegradable plastics. Interview 8 expressed that without a significant fraction of biodegradable plastics in the waste stream, there is no incentive to sort it out. However, without sorting, the biodegradable plastics do not form a fraction that is usable and has value. Interviewee 7 elaborated that when something new is introduced, it’s small in volume and hence it is not economically feasible to sort it out. Instead it is considered as a contaminant, as pollution. He explained “However, because it's considered as a contaminant, there's no market for it to grow, and it never reaches that 25%. But technically, it is very much possible, just as the other plastics, to sort it out and to reprocess it into something new”.

Interviewee 9 expressed a critical concern about the introduction of multiple types of biodegradable plastics in the market. He explained that the introduction of new plastics, in this case biodegradable plastics adds to the existing complexity associated with the sorting and recycling of material. The increase in varieties of plastics would require more intensive sorting efforts, resulting in greater material losses. He emphasized that the focus should be on simplifying the plastics ecosystem and considering the recyclability of plastics, not further complicating it.

Interviewee 2 highlights a concern that biodegradable plastics have to be sorted out of the current plastics waste stream to avoid contaminating these waste streams and affecting the quality of the other plastics. Interviewee 9 further elaborated on the technical complexities associated with sorting and recycling these plastics. He explained that infrared sorting equipment is 90% effective. He explained that biodegradable plastics with its different types poses significant challenges “for all existing recycling streams that are currently being recycled to a higher level because it will simply mean a much more cross-contamination of good recyclable plastics with biodegradable biobased materials which are not compatible with the other plastics”. He stressed that while biodegradable plastics can have added value in certain contexts, these plastics have no functionality in the packaging stream.

Interviewee 3 adds his insight, expressing that in order to sort out biodegradable plastics, there would need to be a purpose for them; “we always ask ourselves if we want to recycle the product, where do we bring it?” It would require building a new chain for recycling biodegradable plastics; where the producers or packaging industry would need to finance the whole chain and the recycling industry aims for recycling at scale. Additionally, for producers to prioritize these plastics over conventional plastics, it would need to be driven by consumer demand and public opinion. These insights from both interviews highlight that the current technical infrastructure and value chain for recycling biodegradable plastics are very under-developed.

When it comes to biodegradable plastic waste found in organic waste bins, interviewees from the waste sector highlight that biodegradable plastics take too long to form compost, due to which they are sieved off. In contrast, Interviewee 7 and 8 counters that some biodegradable plastics have been demonstrated in an industrial composting simulation to degrade faster than orange peels and some organic waste. Interviewee 8 explained that as they break down, they can be re-fed into the compost. However, due to contamination by non-biodegradable plastics, the plastics are removed in the beginning including compostable plastics, thus not allowing them to compost. Another concern further highlighted by Interviewee 4 is that the current standards for biodegradable plastics are outdated, needing revision and adherence to stricter guidelines. Interviewee 2 noted that an added fear that composting facilities have is the risk of other kinds of plastics and microplastics ending up in compost as a result of consumer confusion about biodegradable plastics. These contrasting perspectives highlight a lack of consensus among various stakeholders, which can influence policy development and waste management practices, possibly keeping the system in a locked-in state.

As discussed earlier in this section, consumers and residents pay higher prices for biodegradable plastic products or packaging. Dilkes-Hoffman et al. (2019) highlights that consumers often equate green or sustainable packaging with its end-of-life options such as being reusable, recyclable or biodegradable. Their willingness to pay for green materials can be “more accurately described as a willingness to pay for ‘sustainable’ end-of-life options” (Dilkes-Hoffman et al., 2019). In line with this thinking, people who purchase biodegradable plastic products or packaging do so assuming that these plastics are ending in sustainable end-of-life options. However, biodegradable plastics are currently not recycled or composted; they are instead sent for incineration. Interviewee 3 adds his insight: “The claim is that you have a very environmental friendly product. It ends up in a waste incinerator. So that means that the green claim is not followed up by the infrastructure. So it's not being processed in a way where the claim for the residents is.” This highlights a mismatch between consumer perception and expectation and actual waste treatment of biodegradable plastics.

In the broader context, there are currently no EU or local (municipality level) regulations or policies specifically addressing biodegradable plastic waste. Additionally, Interviewee 3 highlights that legislation is needed to make significant changes in other parts of the value chain for biodegradable plastics. He added that legislation is needed in order to transition the system and create a level playing field against fossil-based plastics.

The inefficiencies identified throughout this section highlight the complexities associated with biodegradable plastics and illustrate how the biodegradable plastic waste management system is not a stand-alone system; in fact, it is a complex system where social actors have significant influence on the efficiency of the technical system and where the technical system influences the social system. Additionally, economic and regulatory factors play a vital role in influencing these sub-systems. The loop diagram in Figure 10 highlights some of these interdependencies described in this section, illustrating how elements within the socio-technical system can influence each other (Note: The ‘+’ symbol indicates a direct influence and ‘-’ symbol indicates an inverse influence).

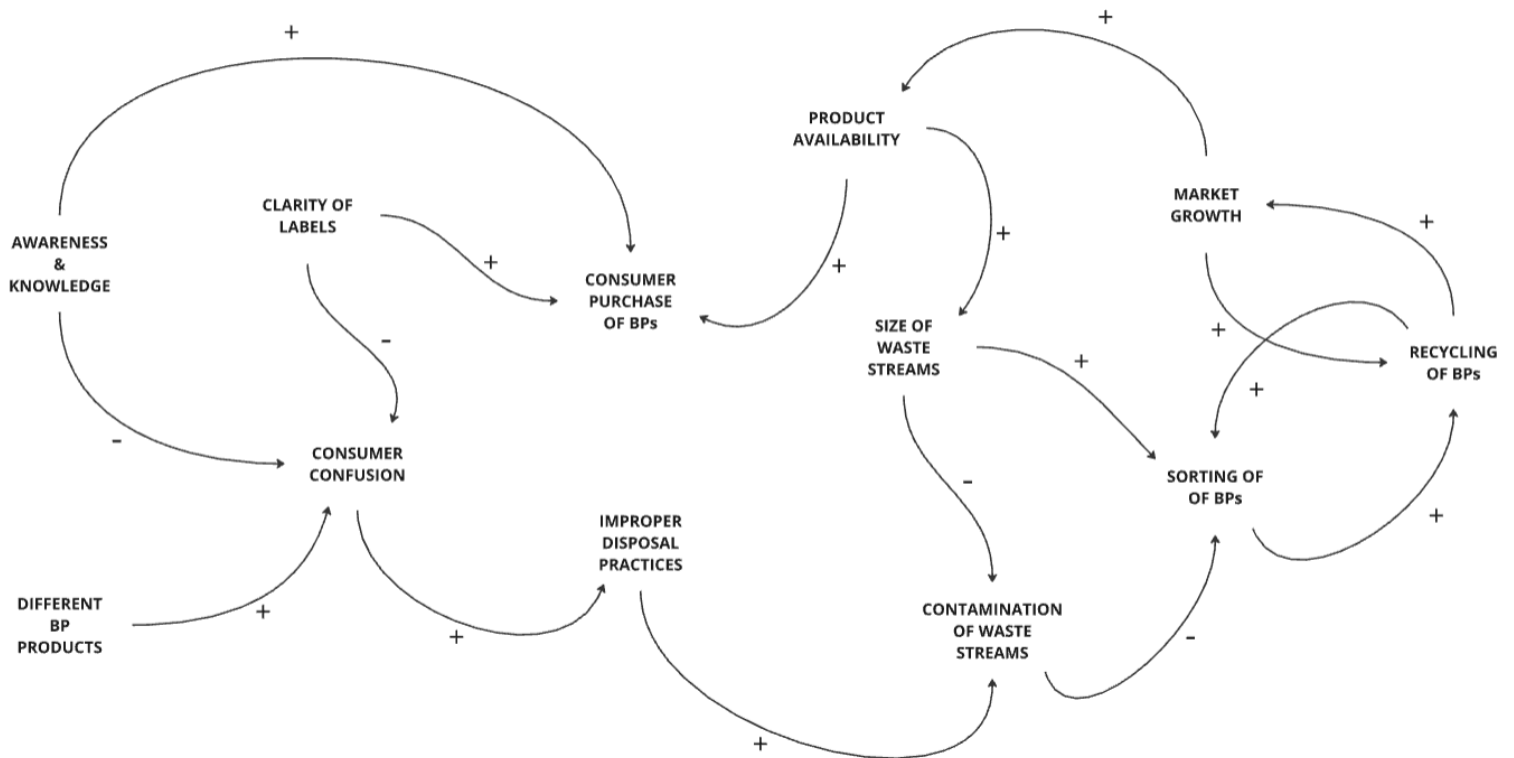


Figure 10: Loop diagram illustrating interconnectedness of some elements of the biodegradable plastic (BP) waste management system (Source: Author)

5.3 Optimization Strategies of the Current Biodegradable Plastic System (R4)

This section explores strategies for optimizing the current biodegradable plastic waste management system in Leeuwarden. Building upon the previously identified strengths and inefficiencies of the system combined with perspectives of residents and other key stakeholders, this section utilizes the Environmental Design Framework (introduced in the methodology chapter). This framework provides a structured approach to identifying strategies to optimize the waste management system for biodegradable plastic waste. This is followed by a discussion on the feasibility of these strategies specific to Leeuwarden's context and at a broader level, the Netherlands.

The survey revealed areas of improvement for the biodegradable plastic waste management system in Leeuwarden identified by residents as depicted in Figure 11. A significant majority of respondents highlighted the need for clearer labelling on biodegradable plastic packaging. A large proportion suggested an increase in the number of conveniently located disposal/collection points. Additionally, a significant number of respondents selected increase in information campaigns from the municipality or waste management company and clear disposal information on the packaging. Interestingly, financial incentives was the least chosen option, indicating that respondents may be more motivated by convenience, information and environmental behaviour. Several respondents provided additional insights; one respondent mentioned using only biodegradable plastics while another suggested stimulating manufacturers to use biodegradable plastics. These insights highlight the perceived importance of biodegradable plastics among some respondents. A few others requested a separate bin or collection point for collecting plastic. Furthermore, various respondents emphasized the need for more awareness, knowledge and information campaigns to educate residents about biodegradable

plastics and how to recognize them. These various suggestions for improvement address the concerns and inefficiencies identified in the previous section.

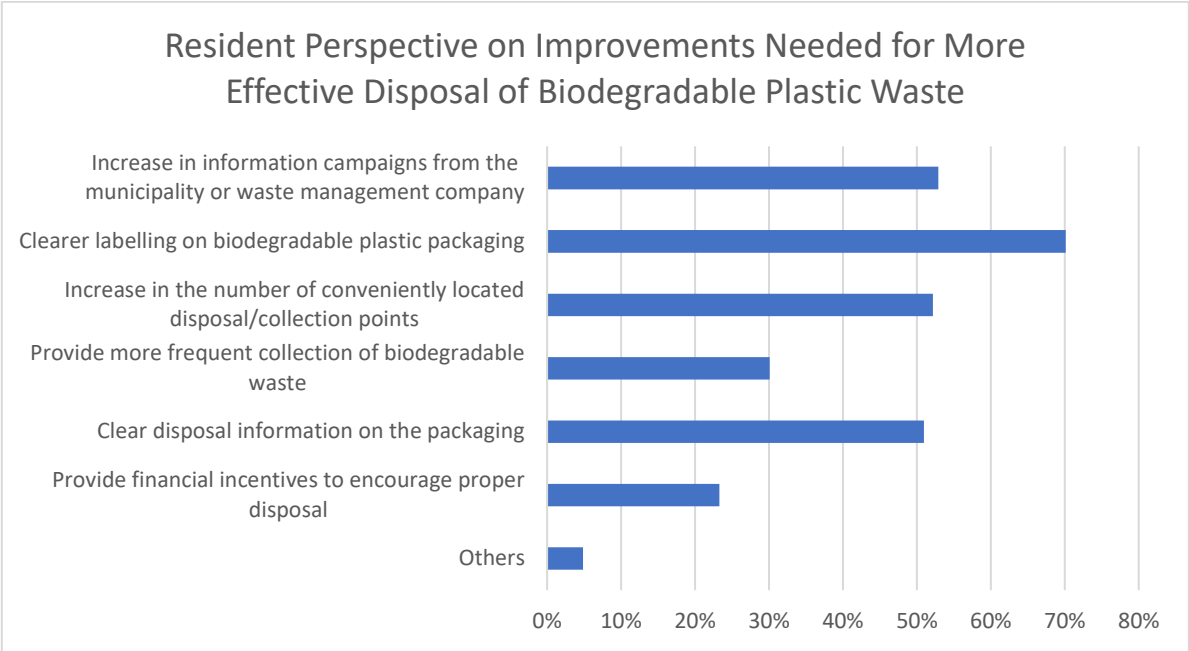
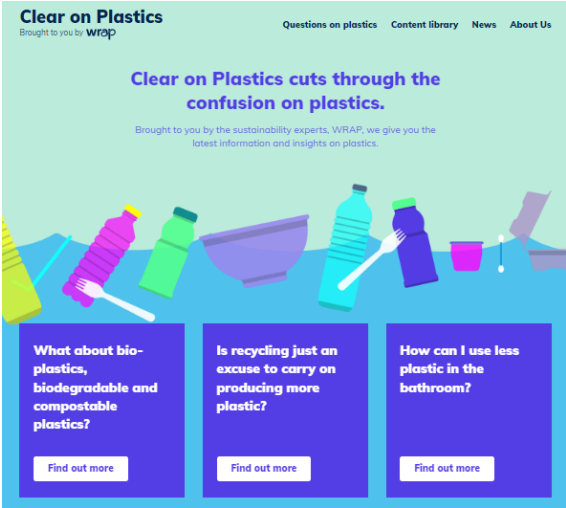




Figure 11: Resident perspective on improvements needed for more effective disposal of biodegradable plastic waste

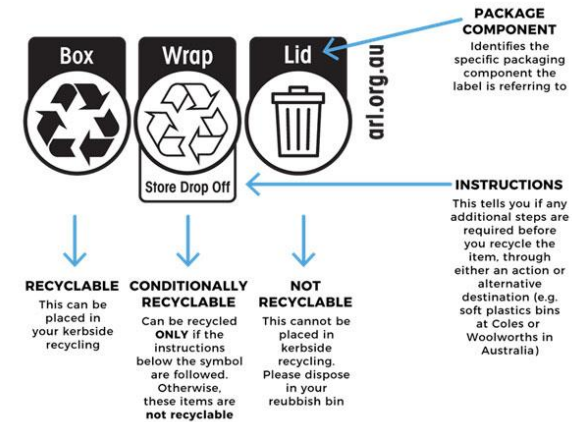
The Environmental Design Framework (Kaplan et al., 2007) as described in the methodology chapter can help identify potential strategies to optimize the biodegradable plastic waste management system. The first step involves utilizing insights on the strengths, inefficiencies and stakeholder suggestions for improvement identified throughout the discussion section, which can help inform the needs, goals and key domains of quality of life required for effective management of biodegradable plastic waste. These goals and key domains are then translated into key desired characteristics or attributes in the next step. These characteristics or attributes guide the development of strategies within the physical and organizational environments of the biodegradable plastic waste management system. Finally, the last step involves selecting real-life examples or case studies to show the successful or unsuccessful implementation of these strategies. These examples can be adapted to address the specific challenges and context of Leeuwarden or more broadly, the Netherlands. While some of these examples come from business or industrial settings, their underlying design concepts can be applied to improve residential waste management systems. Following these steps, the optimization strategies are depicted in Table 5.

Table 5: Optimization strategies using the Environmental Design Framework













Experiences/Domains of Quality of Life	Design Principles	Design Concepts	Design Applications
Public awareness and knowledge	Provide clear and accessible information (to address knowledge gaps about biodegradable plastics and proper disposal practices)	<ul style="list-style-type: none"> Public awareness campaigns and educational initiatives through multiple channels such as online platforms, social media, workshops and events Collaboration with environmental groups or activists to disseminate information 	<ul style="list-style-type: none"> Reports and briefings on biodegradable plastics by various institutions such as European Commission, European Environment Agency (EEA), Greenpeace, etc. Report on biodegradable plastics published by Beyond Plastics, a nationwide non-profit project based at Bennington College in Vermont, USA comprising of environmental policy experts and grassroots advocates seeking to educate policy makers and public on plastic pollution crisis Clear on Plastics social media led campaign by The Waste and Resources Action Programme (WRAP) supported by the UK Plastics Pact to give citizens evidence-based information on plastics and sustainability to encourage informed decision-making (WRAP, n.d.)  <ul style="list-style-type: none"> Dsolve’s social media campaign week on biodegradable plastics (used for marine applications) where experts addressed concerns of environmental actors; as well as other dissemination channels such as presentations, flyers and factsheets at events and conferences, through social media videos and podcasts on industry perspectives (Dsolve, 2023)

			<ul style="list-style-type: none"> • Pilot learning path for raising awareness about bioplastics among high school students in Bologna, Italy; which involved imparting 32 high school students with relevant knowledge and providing hands-on experimental experience. A crucial component of the learning process was tasking students with creating products to disseminate the acquired knowledge to peers and wider audience (Torreggiani et al., n.d.) • Summer school held at University of Bologna as part of BIO-PLASTICS EUROPE project with various students, researchers and professionals participating in the five-day intensive programme; which involved exploration of innovation business models and bio-based plastics within the circular economy paradigm through addressing real-world challenges (Bio-Plastics Europe, 2023) 
Clarity of labelling and disposal information	Provide clear and standardized labels with accurate disposal information (to address resident confusion around biodegradable plastics and correct disposal)	<ul style="list-style-type: none"> • Standardized labelling systems • Clear guidelines for disposal (labelling them biodegradable or bio-based or compostable is not enough) 	<ul style="list-style-type: none"> • Improved Seedling logo indicating 'Industrially Compostable' instead of only 'Compostable' in the previous version (European Bioplastics, n.d.-c); extended messaging is recommended to prevent improper disposal  <div data-bbox="1841 1098 2007 1342" style="border: 1px solid black; padding: 5px;"> <p>Intended for industrial composting only.</p> <hr/> <p>Check if accepted by your local biowaste disposal service.</p> <p>NO PROOF OF HOME COMPOSTABILITY.</p> <p>DO NOT LITTER!</p> </div>

- [Australasian Recycling Label](#), an evidence-based national labelling scheme providing clear on-pack disposal and recycling information per component to consumers in Australia and New Zealand; powered by Packaging Recyclability Evaluation Portal (PREP) – online tool that assesses product recyclability; acknowledged in the National Waste Policy Action Plan and National Plastics Plan in Australia; accepted by New Zealand Ministry for Environment as preferred labelling method; voluntary scheme adopted by 800 organizations; 255,000 SKUs carry the ARL (Australasian Recycling Label, n.d.; Planet Ark, n.d.)



- [How2Recycle](#) and [How2Compost](#) voluntary, standardized labelling, providing clear on-package disposal information to consumers in US and Canada; developed by a Sustainable Packaging Coalition working group; designed to comply with US Federal Trade Commission (FTC) Green Guides; thorough assessment carried out by How2Recycle team before labelling; 800 members consisting of consumer facing brands and packaging suppliers; dynamic label and Guidelines for Use adapting to policy changes around labelling and recyclability; endorsed by various government

			<p>agencies and non-profit organizations such as New York City Department of Sanitation, North Carolina Department of Environment and Natural Resources, StopWaste, etc. (How2Recycle, n.d; Moore, 2024; Stop Waste, n.d.)</p> <div style="display: flex; justify-content: space-around; align-items: center;"> <div style="text-align: center;">  </div> <div style="text-align: center;">  </div> <div style="text-align: center;">  </div> </div> <ul style="list-style-type: none"> Disposal guide logos (Weggooiwijzer logos) provided in the Netherlands; developed by The Netherlands Institute of Sustainable Packaging (KIDV); based on the national yes/no list; the use of the logos is voluntary (Netherlands Institute for Sustainable Packaging, 2024) <div style="display: flex; justify-content: center; align-items: center; gap: 10px;"> <div style="text-align: center;"></div> <div style="text-align: center;"></div> <div style="text-align: center;"></div> <div style="text-align: center;"></div> <div style="text-align: center;"></div> </div> <div style="display: flex; justify-content: center; align-items: center; gap: 10px; margin-top: 10px;"> <div style="text-align: center;"></div> <div style="text-align: center;"></div> <div style="text-align: center;"></div> <div style="text-align: center;"></div> </div>
Efficient sorting behaviour among residents	Increase resident engagement and participation in waste separation (to improve sorting and disposal practices)	<ul style="list-style-type: none"> Educational/informational campaigns on proper sorting and disposal especially for biodegradable plastic products with different recommended disposal methods Clear labelling systems with disposal instructions 	<ul style="list-style-type: none"> Consumer behaviour trial involving 120 households in Medway, UK conducted by Compostable Coalition UK demonstrated a significant five-fold increase in correct disposal of compostable packaging when clear labels and educational materials were provided; along with increase in food waste disposal and reduced contamination. Additionally, composting trials at Envar, a large composting site in UK tested 13 tonnes of compostable materials under industrial composting, demonstrating successful biodegradation with the compost meeting high quality standards (Packaging Europe, 2024)

- Provision of incentive schemes to improve sorting behaviour


- A [national information campaign](#) led by SPHERE, a household packaging supplier to aid local authorities in implementing biowaste sorting solutions at source by providing bio-sourced compostable bags for pre-collection and establishing collection systems; aimed at turning biowaste into a resource; the tagline for the campaign ads being “The solution is in the bag” (SPHERE, 2022)




- The '[Un sacco et\(n\)ico](#)' project, a research-action and training project in Milan, Bergamo, and Brescia promoted by Economia e sostenibilità (EStà) to encourage separate waste collection, reduction of single use plastics and promotion of compostable products using a linguistic-cultural mediation approach targeting ethnic catering companies (In collaboration with biodegradable plastic supplier and local administration) (Economia e sostenibilità, n.d.; Comune di Milano, 2022)



- Material recovery facility (MRF) tours at Westchester County, New York to educate visitors on recycling purpose and benefits; available free of charge to school classes, scout troops and special interest groups (Westchester County, n.d.)

			<ul style="list-style-type: none"> • ‘Beyond the Kerb’ community tours of waste and recycling sites to inform residents where their waste including recyclables and organic waste goes after collection from the kerb; conducted by Keep South Australia Beautiful (KESAB) and subsidized by their councils (KESAB, n.d.)  <ul style="list-style-type: none"> • GREEN\$ Electronic Participation Incentive Scheme - GREEN\$ (Greeny Coins) smart card launched by Environmental Protection Department (EPD) in Hong Kong to motivate public participation in recycling by bringing their recyclables to community recycling facilities/stations/spots; citizens bringing atleast 2 kg of recyclables can register for the GREEN\$ smart card; they can show the card or GREEN\$ app during subsequent recycling submissions and earn GREEN\$ points which can be redeemed for small gifts (Plastic Smart Cities (WWF), 2023; Hong Kong Waste Reduction Website, n.d.) • Voluntary recycling incentive scheme introduced by Bracknell Forest Council in Southern England to boost household curbside recycling participation; residents opting into the scheme received an "e+ card" to collect points for eligible recycling practices, which can be redeemed for leisure rewards like discounts at sports centres; successful implementation with 11,000 households participating and residual waste reduction by 1000 tonnes (Plastic Smart Cities (WWF), 2023)
Efficient communication and collaboration between stakeholders	Encourage stakeholder engagement to increase information sharing and collaborative efforts to increase system efficiency	<ul style="list-style-type: none"> • Ensure residents are made aware of available feedback mechanisms • Feedback mechanisms to address resident concerns and gather resident perspectives • Collaborative initiatives 	<ul style="list-style-type: none"> • Collaboration between Vegware, a compostable packaging producer with waste sector in Scotland, Bristol, Gloucester and Worcester (UK) to make collection of compostable packing more accessible; partners with local waste operators and available composting facilities to expand waste collection routes (GENeco, n.d.; Vegware, n.d.-a)

<p>Developed infrastructure and advanced treatment solutions</p>	<p>Invest in and develop infrastructure for collection, sorting and recycling</p>	<ul style="list-style-type: none"> • Extended producer responsibility and reverse logistics; or use of recycled biodegradable plastics by producers (to finance the recycling chain which in turn influences scale up of sorting and recycling infrastructure) • Provision of convenient collection points for plastic (in general) or biodegradable plastics (as volume increases) 	<ul style="list-style-type: none"> • Vegware’s Close the Loop initiative which is their dedicated waste collection service collecting used Vegware packing and food waste for commercial composting in the UK; works with small businesses and venues and partners with waste providers or facilities where the waste is converted into high grade compost under 12 weeks (Vegware, n.d.-b)  <ul style="list-style-type: none"> • The Compost Collective, a circular waste collection and composting network, launched by Port Kitchen at Shoreham Port; partners with Vegware and Paper Round to create a network of local drop-off points where consumers (businesses) can return their compostable waste; Vegware provides the fully compostable packaging while Paper Round provides on-site bins and frequent collections (Sussex Chamber of Commerce, 2024) • Biorepack, an EPR consortium established to manage and promote organic recycling of compostable and biodegradable plastic packaging into compost or biogas; jointly managed by a government and business consortium; implemented a reduced environmental contribution fee to support bioplastics and improve the infrastructure for their organic recycling (Expra, n.d.) • Plant in Belgium recycling PLA plastics by Looplife Polymers though in small volume (The Danish Environmental Protection Agency, 2020) • Italy has high acceptance of compostable plastics; has composting and anaerobic digestion (AD) facilities equipped to effectively manage compostable plastics; the use of the dry AD process followed by a secondary maturation phase provides sufficient time for full biodegradation. Additionally, the composting facilities must operate for atleast 90 days (The Danish Environmental Protection Agency, 2020)
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The strategies outlined in the above table provide a structured framework for optimizing the biodegradable plastic waste management system, drawing inspiration from real world examples. However, it's essential to consider Leeuwarden's existing infrastructure and waste management practices to determine whether successful implementation of these strategies is possible in Leeuwarden.

Leeuwarden has established public awareness campaigns as a joint collaborative effort between the waste management company and the municipality to influence residential behaviour, though these campaigns are primarily focused on other waste streams. Additionally, the municipality collaborates with schools on various initiatives. These existing efforts can be leveraged to improve public awareness of biodegradable plastics and their proper disposal as the production and use of these plastics continue to grow. Integrating public education of biodegradable plastics into existing campaigns can help address the significant knowledge gaps identified in Section 5.2. These initiatives can be effectively implemented when management of biodegradable plastics become a priority for the city. Bridging these knowledge gaps is crucial to avoid improper disposal practices that can have far reaching consequences across the system, as illustrated by Figure 10 in Section 5.2. Additionally, public awareness and educational campaigns have the potential to not only influence disposal behaviour but also consumption and market demand for biodegradable plastics.

In terms of collection points, it is currently challenging to envision Leeuwarden adopting separate collection points specifically for biodegradable plastic waste. The city has maintained a post-collection separation system since 2007, achieving a high recovery rate of 78%. This system indicates a path dependency, making it less likely to make significant changes due to its successful results. However, the example of the DIFTAR system which was introduced to improve residential sorting behaviour indicates that the city has a history of self-adaptation, suggesting that changes could be made if and when biodegradable plastic usage increases. While Leeuwarden already has bring-back collection schemes for plastic bottles and other materials, policy makers can draw inspiration from innovative incentive-based schemes such as the GREEN\$ electronic participation and e+ card schemes introduced in Hong Kong and UK, respectively, to encourage recycling through non-monetary rewards.

It is important to emphasize that the biodegradable plastic waste management system is a complex socio-technical system that requires joint optimization of the social and technical sub-systems. Optimizing one sub-system without considering the other can result in unintended consequences throughout the system. Considering the intricate interactions and interdependencies between the various social and technical components of the system, interventions cannot be implemented in isolation. For example, increased awareness campaigns may influence positive attitude towards biodegradable plastics, possibly resulting in more biodegradable plastics entering waste streams in a system where its infrastructure is not equipped to deal with an increased flow. Therefore it is essential to jointly optimize both the social and technical sub-systems.

Implementing other optimization strategies require system-wide changes and collaboration among various stakeholders including the government. While reaching a consensus can be challenging due to differing priorities and interests, the case of the compostable tea bags in the Netherlands illustrates that such collaboration is possible. Despite initial debates and disagreements, tea bag and coffee pad producers successfully collaborated with the waste sector with the involvement of government to address a broader issue of waste contamination due to improper residential behaviour, thus taking corrective action.

While the Netherlands has a labelling system that provides disposal information, there is limited data in the Weggooiwijzer disposal guide on the extent on voluntary adoption by organizations, making it

difficult to determine if these voluntary labels are becoming standardized. Both survey responses and interviews highlight issues with labelling, particularly regarding the lack of clear disposal information. This may suggest a misalignment or inefficiency in design that would require further investigation. In contrast, the Australasian Recycling Label (ARL) and the How2Recycle labels have been widely adopted by 500-800 organizations, though this number might be indicative of size of the countries. These labelling systems have rigorous verification processes and are endorsed by governments and non-profit organizations, influencing their wide spread adoption. This illustrates another example of social and technical interactions influencing each other. Additionally, the Netherlands could enhance its logos by including extended messaging especially for compostable and biodegradable products to prevent improper disposal. Collaborations with biodegradable plastic producers and the government could help establish standardized labelling systems.

Changes in the waste infrastructure for biodegradable plastics in the Netherlands can be challenging due to the lock-in effect and the chicken and egg dilemma. There is an underlying opposition to biodegradable plastics (for specific applications) within the waste sector due to very valid concerns over contamination of both organic and plastic waste streams as well as the complexities associated with handling different types of biodegradable plastics. Some interviewees see no value in biodegradable plastics within waste management while other interviewees suggest that a sufficient volume of biodegradable plastics such as PLA (Polylactic acid) together with extended producer responsibility could incentivize investments in sorting and recycling infrastructure. The insufficient market demand for biodegradable plastics and the lack of sorting/recycling infrastructure creates a circular dependency, which would require policy interventions and extensive collaboration between various stakeholders to overcome this barrier. It is also crucial to incorporate end-of-life considerations during product design.

Furthermore, the cases of UK and Italy where compostable bags are being used to reduce food waste highlight that biodegradable plastics, more specifically compostable plastics have the potential to be composted. In the Netherlands, there are conflicting perspectives on the degradation timeline of biodegradable plastics and their feasibility for composting. Establishing harmonized standards for composting may be necessary for wider adoption. Furthermore, a case study could be conducted to explore the factors influencing the acceptance of compostable plastics in Italy.

When developing optimization strategies and collaborative initiatives, it is important to balance innovation without hindering existing waste management system, which is already a complex system even without the introduction of biodegradable plastics. Due to the complexity of this system with its various interactions and interdependencies, it is important to consider any unintended consequences or effects on other parts of the system before implementing interventions intended to optimize the system. Implementation of these strategies requires careful monitoring and evaluation to assess the effectiveness of these strategies.

5.4 Contribution of the Study

This study contributes to the existing body of research on waste management by providing an in-depth analysis of biodegradable plastic waste management by applying a socio-technical systems perspective. This study provides valuable insights into the complex interactions and interplay between various actors and components within the system. Furthermore, analyzing the system through the lens of complexity theory provides valuable insights into feedback loops and interconnections that are not obvious, highlighting how one part of the system can significantly influence other components. This study demonstrates the importance of studying and analyzing a large system such as waste infrastructure through complexity and socio-technical systems lenses. The insights gained from the

application of the Environmental Design Framework to the context of biodegradable plastic waste management can inform policy makers and key stakeholders in developing informed strategies for effective management of biodegradable plastics.

5.5 Limitations and Future Research

This study utilized convenience sampling due to time constraints. While efforts were made to gather a diverse range of respondents through distributing surveys at various locations and gathering responses across various gender and age groups, the sample may not fully represent the entire population of Leeuwarden. Future research should consider using more reliable sampling methods such as random sampling or stratified sampling to get a more representative sample of the population. The age group 45-54 years is underrepresented in this study; future studies should investigate whether the perceptions, knowledge and behaviours regarding biodegradable plastics differ significantly within this demographic. Additionally, while surveys were distributed in English and Dutch, it is important to ensure that further studies include segments of the population that do not speak either of these languages.

Furthermore, while the surveys did include open-ended questions to gain additional insights, the structured format of the survey may have limited the depth of information gathered on certain topics. Future research could benefit from conducting in-depth interviews with residents or focus groups to gain a more in-depth understanding of residents' perceptions, knowledge and behaviours.

Longitudinal studies should also be considered to study the temporal aspects of the biodegradable waste management socio-technical system, in order to track changes in resident knowledge and behaviour over time and assess the long-term effectiveness of implemented interventions or optimization strategies. These studies could investigate how resident perception and behaviour evolve over time in response to awareness campaigns, policy changes and other interventions or strategies designed to improve biodegradable plastic waste management; thus providing insights into the effectiveness of these interventions and identifying further areas of improvement. Future research could also explore the drivers that can facilitate the transition of the current system towards better integration of biodegradable plastics, as recommended by Interviewee 3 from the waste management company.

6. Conclusion

This research analyzed the biodegradable plastic waste management system in Leeuwarden, identifying its strengths and inefficiencies from a socio-technical systems perspective. Through a mixed-methods approach, resident surveys and interviews with key stakeholders such as the waste management company and the municipality provided key insights into the current system.

The system demonstrates various strengths such as a baseline level of awareness among residents, resident engagement with current collection infrastructure and active waste separation. The system has established communication channels, public awareness campaigns and information dissemination initiatives to positively influence residential waste separation behaviour. Most importantly, the system has demonstrated a capacity for self-adaptation, constantly evolving in response to challenges with feedback loops that reinforce desired behaviour or correct undesired ones.

However, the biodegradable plastic waste management system has several critical inefficiencies and challenges. There are significant knowledge gaps and confusion among residents; with residents having limited knowledge about biodegradable plastics, terminologies and proper disposal methods. This lack of knowledge leads to confusion and improper disposal practices among residents, contaminating certain waste streams and thus hindering the efficiency of the overall waste management system. Analyzing the system through the socio-technical perspective demonstrates the interactions and influences of social and technical components on each other.

The technical infrastructure and value chain for biodegradable plastics are significantly underdeveloped. This is highlighted by a lack of dedicated sorting infrastructure or recycling facilities for biodegradable plastics due to the low volume of their waste stream and a lack of incentivization for packaging producers to prioritize recycling of these plastics. This creates the chicken and egg dilemma where biodegradable plastics are not sorted and recycled due to their low volumes and their low volumes remain so due to an absence of recycling options. Though biodegradable plastics have the potential for composting due to its biodegradability, their rate of degradation doesn't align with the timeline expected by the waste sector for organic waste composting. As a result, biodegradable plastics are not recycled or composted (in line with the EU waste hierarchy). Instead, they are sent for incineration and converted to heat and electricity. This highlights a mismatch between consumer perception and actual waste management practices. Consumer willingness to pay for these products assumes sustainable end-of-life options; however, the current infrastructure doesn't support the possibility of such options.

There are limited policies or regulations for biodegradable plastic waste. Furthermore, there is a lack of legislation for biodegradable plastics that creates an uneven playing field and discourages investment in the value chain for these plastics. These various inefficiencies highlight the complexities that come with biodegradable plastics and the complex interactions between the social actors, the technical infrastructure, the market, economic factors and regulations. Tackling these inefficiencies would require structural changes at various levels of the value chain.

It is crucial for the current system to be optimized in order to handle the projected increase in production of biodegradable plastics in the coming years. Public education campaigns targeting residents are required to improve resident knowledge about biodegradable plastics and encourage proper disposal behaviours. Collaboration with producers and packaging industry is necessary to develop clear and standardized labelling systems that provide accurate disposal information. Labels should go beyond indicating the type of plastic; they should provide clear disposal guidelines especially for different biodegradable products with different disposal methods. Additionally, investment into

development of sorting and recycling infrastructure is needed in order to effectively handle biodegradable plastic waste as the volume of this waste stream increases. Finally, policy interventions and extensive collaboration among stakeholders is required to overcome system-wide challenges.

It is important to recognize that the biodegradable plastic waste management system is a complex system with diverse stakeholders, multiple feedback loops between system components and uncertainties about the future of biodegradable plastics. While this complex socio-technical system can be managed and optimized through strategies, it cannot be fully controlled. Instead, it will continue to adapt and evolve in response to societal and environmental changes, thus requiring continual review and revision of the system and its design.

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Appendix A: Summary of Survey Data

Table A1: Detailed summary of survey questions and responses

Survey Question	Responses
Q1: Have you heard of biodegradable plastics before this survey? (412 respondents)	Yes: 319 responses (77%)
	No: 73 responses (18%)
	Not sure: 20 responses (5%)
Q2: Do you currently separate your household waste into different bins? (410 respondents)	Yes: 306 responses (75%)
	No: 21 responses (5%)
	Sometimes: 62 responses (15%)
	Separate bins are not provided: 21 responses (5%)
Q3: Do you think that the bio-based plastics and biodegradable plastics are the same thing? (412 respondents)	Yes: 30 responses (7%)
	No: 202 responses (49%)
	Not sure: 180 responses (44%)
Q4: In general, which of the following methods do you think is most suitable for disposing of biodegradable plastics? (411 respondents)	Composting at home: 84 responses (20%)
	Throwing in organic waste bin: 157 responses (38%)
	Throwing in general waste bin: 85 responses (21%)
	Disposing in a bin or bag designated specifically for plastic waste: 143 responses (35%)
	Having a separate collection bin or collection point for biodegradable plastics: 176 responses (43%)
	Don't know: 30 responses (7%)
	Others: 14 responses (3%)
Q5: How important do you think it is to have separate collection systems for biodegradable plastics? (409 respondents)	Very important: 116 responses (28%)
	Important: 177 responses (43%)
	Neutral: 98 responses (24%)
	Unimportant: 6 responses (1%)
	Very unimportant: 12 responses (3%)
Q6: How confident are you in your ability to recognize biodegradable plastic labels? (411 respondents)	Very confident: 30 responses (7%)
	Somewhat confident: 117 responses (28%)
	Neutral: 89 responses (22%)
	Somewhat unconfident: 92 responses (22%)
	Very unconfident: 61 responses (15%)
	Don't know: 22 responses (5%)
Q7: Do you have separate bins or containers for biodegradable plastic waste in your neighbourhood? (409 respondents)	Yes: 36 responses (9%)
	No: 271 responses (66%)
	Not sure: 102 responses (25%)
Q8: Do you think that the terms "bioplastics" and "biodegradable plastics" can be used interchangeably? (408 respondents)	Yes: 85 responses (21%)
	No: 154 responses (38%)
	Not sure: 169 responses (41%)

Q9. To your knowledge, how often do you purchase products and/or packaging with biodegradable plastic? (410 respondents)	Always: 4 responses (1%)
	Often: 55 responses (13%)
	Sometimes: 205 responses (50%)
	Never: 25 responses (6%)
	Don't Know: 121 responses (30%)
Q10. If you purchase or use products and/or packaging with biodegradable plastic, how do you currently dispose of biodegradable plastic waste in Leeuwarden? (264 respondents; those who answered 'Never' or 'Don't know' to Question 9 were excluded from these calculations)	Composting at home: 12 responses (5%)
	Throwing in organic waste bin: 86 responses (33%)
	Throwing in general waste bin: 140 responses (53%)
	Disposing in a bin or bag designated specifically for plastic waste (if available in your area) : 33 responses (13%)
	Others: 4 responses (2%)
Q11. In your opinion, what are some of the challenges residents in Leeuwarden face in disposing biodegradable plastics properly? (411 respondents)	Lack of easily accessible collection bins or collection points for biodegradable plastic waste: 240 responses (58%)
	Lack of clear disposal information on the packaging: 231 responses (56%)
	The current system doesn't collect enough biodegradable packaging to justify a separate bin: 121 responses (29%)
	Difficulty identifying biodegradable plastics due to unclear labelling: 202 responses (49%)
	Low priority from waste management company or municipality for managing biodegradable plastic waste: 135 responses (33%)
	Communication about proper disposal of biodegradable packaging from the waste management company is lacking: 173 responses (42%)
	Managing too many different waste streams for proper segregation is overwhelming: 84 responses (20%)
	Others: 36 responses (9%)
Q12. What improvements would make it easier for you to dispose of biodegradable plastics properly? (412 respondents)	Increase in information campaigns from the municipality or waste management company: 218 responses (53%)
	Clearer labelling on biodegradable plastic packaging: 289 responses (70%)
	Increase in the number of conveniently located disposal/collection points: 215 responses (52%)
	Provide more frequent collection of biodegradable plastic waste: 124 responses (30%)
	Clear disposal information on the packaging: 210 responses (51%)
	Provide financial incentives to encourage proper disposal: 96 responses (23%)
	Others: 20 responses (5%)
Q13. Do you believe that biodegradable plastics break down completely into harmless materials under all conditions? (412 respondents)	Yes: 62 responses (15%)
	No: 149 responses (36%)
	Not sure: 201 responses (49%)

Q14. How do you currently get waste disposal updates from the waste management company? (410 respondents)	App notifications: 143 responses (35%)
	Information letters: 139 responses (34%)
	Social media: 42 responses (10%)
	Waste management company website: 59 responses (14%)
	I don't know: 93 responses (23%)
	Others: 39 responses (10%)
Q15. Do you know of any ways to provide feedback to the waste management company about the current waste disposal system? (408 respondents)	Yes: 91 responses (22%)
	No: 317 responses (78%)
	If yes, please specify how: 56 responses out of 91 respondents who said yes
QA. What is your age? (410 respondents)	Under 18 years: 0 responses (0%) (Exclusion category)
	18-24 years: 76 responses (19%)
	25-34 years: 95 responses (23%)
	35-44 years: 76 responses (19%)
	45-54 years: 35 responses (9%)
	55-64 years old: 62 responses (15%)
	65-74 years old: 45 responses (11%)
	75 years or older: 20 responses (5%)
Prefer not to say: 1 responses (0%)	
QB. What is your gender? (410 respondents)	Male: 187 responses (46%)
	Female: 217 responses (53%)
	Non-binary: 4 responses (1%)
	Prefer not to say: 2 responses (0%)
QC. What is your household type? (409 respondents)	Single-person household: 122 responses (30%)
	Multi-household with children: 132 responses (32%)
	Multi-household without children: 106 responses (26%)
	Shared living (Eg. roommates, housemates, etc.) : 47 responses (12%)
	Prefer not to say: 2 responses (0%)
<i>Note: Questions 4, 10, 11, 12 and 14 allowed respondents to select multiple answers. The number of respondents varies for each question due to some missing responses. The percentage calculations are based on the number of complete responses received for each survey questions; any missing responses were excluded from the calculations.</i>	

Appendix B: Interview Questions by Stakeholder Group

1. Waste Sector:

- Can you describe the current systems and processes that are in place for collecting biodegradable plastic waste in Leeuwarden?
- How does your organization sort and separate biodegradable plastics from other waste streams, especially other types of plastics?
- What technologies or treatment processes are used for biodegradable plastic waste?
- What are some challenges that your organization faces in the collection, sorting and treatment of biodegradable plastics?
- What is the feasibility of biodegradable plastics for composting, reuse and recycling? What are the challenges in composting and recycling biodegradable plastics?
- How does your organization communicate with residents regarding the proper disposal of biodegradable plastics?
- What are some issues (if any) that you face in terms of resident confusion or improper disposal of biodegradable plastics?
- What communication channels or strategies do you use to collect feedback from residents about your waste management processes and how do you incorporate this feedback into making improvements to the waste management system?
- How does your organization collaborate with other stakeholders (like municipalities, industry associations, biodegradable plastic suppliers) on biodegradable plastic waste management?
- In your opinion, what improvements are needed to optimize the management of biodegradable plastic waste in Leeuwarden?
- Are there any concerns or considerations your organization has regarding the soon-to-be widespread adoption of biodegradable plastics?

The above interview questions served as a general guide. Depending on the role of the interviewee and the type of waste processing organization within the waste sector in Leeuwarden and the Netherlands, certain questions were adapted and explored in greater depth.

2. Municipality:

- Can you provide an overview of the current local regulations and policies regarding biodegradable plastic waste management in Leeuwarden?
- Are there any upcoming policy changes or new regulations being considered for biodegradable plastics?
- What are the main challenges the municipality faces in managing biodegradable plastic waste and what steps are being taken to address them?
- Can you describe the collaboration and coordination between the municipality and waste management companies regarding biodegradable plastic waste to ensure proper collection, sorting, and processing of biodegradable plastics?
- Are there any challenges or successes you can share about this collaboration?
- What strategies does the municipality use to engage residents in proper biodegradable plastic waste management?
- How do you measure the effectiveness of these engagement and educational efforts?
- How does the municipality gather feedback from residents regarding waste management practices? How do you incorporate these feedback?
- What suggestions do you have for improving the current waste management system, particularly concerning biodegradable plastics?

3. Biodegradable Plastics Industry (Including Researchers):

- What are the most common types of biodegradable plastics in use today and what are their primary applications?
- In your opinion, what are the current advantages and limitations of biodegradable plastics compared to traditional plastics? Any specifically relevant to waste management?
- Can you provide some insight into the biodegradation of biodegradable plastics in open environments and controlled environments like industrial composting facilities?
- Would you recommend separate collection systems as these materials become more prevalent?
- Do you think there is adequate infrastructure currently in place to sort biodegradable plastics from other plastics?
- What are the main challenges and opportunities in both composting and recycling biodegradable plastics at an industrial scale and what advancements are needed to improve these processes?
- In your opinion, what are the best end-of-life options for biodegradable plastics? Are there specific conditions under which one end-of-life option is preferable over another?
- What are some potential inefficiencies that might arise specifically in managing biodegradable plastic waste compared to traditional plastics?
- What are the current challenges and potential solutions for implementing effective reverse logistics for biodegradable plastics?
- What do you think would be needed to better optimize the waste management system to integrate biodegradable plastics into the existing waste stream?
- Where do you see future research or investments regarding biodegradable plastics in general, and related to waste management?

Appendix C: Thematic Codebook

The thematic codebook can be accessed via the following link:

https://drive.google.com/drive/folders/1WG9uB9iE34PFAMchcGan4V26IRUY91B7?usp=drive_link