# The Path to Plastic-Free Soil: Strategic Frameworks for Biowaste Composting


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# Acronyms and Abbreviations

| Acronym | Full name |
|---|---|
| **CE** | Circular Economy |
| **CST** | Critical Systems Thinking |
| **FVH** | Forum Virium Helsinki Oy |
| **GHG** | Grant Agreement |
| **GDPR** | General Data Protection Regulation |
| **PE** | Polyethylene |
| **PET** | Polyethylene Terephthalate |
| **PP** | Polypropylene |
| **PPWR** | Packaging and Packaging Waste Regulation |
| **TRL** | Technology Readiness Level |

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## Executive Summary

This report presents the outcomes of a collaborative research project between the EU-funded TREASoURcE project and the Aalto University International Design Business Management (IDBM) master's programme. This project tackles the challenge of plastic contamination in industrial biowaste composting and it was approached through the perspective of the reference company Kekkilä, Finland's leading manufacturer in landscaping products. The goal of the project was to identify cost-effective plastic separation methods that can be used at an industrial scale environment. The results of the project are publicly available and replicable.

The contaminated material that Kekkilä's facility in Joutseno receives for soil production comes mostly from grocery stores where regulation and lack of appropriate resources allow for food products to be disposed in their original packaging. The company has not found an effective way to remove the plastics from packaged biowaste that causes some plastic residues in the final product after their current separation and composting process. This compromises compost quality, leads to customer complaints, weakens brand image, and raises long-term environmental concerns such as microplastics in soil. While their products significantly meet current regulatory standards, the quality expectations from consumer side highlight the need for more effective solutions.

The problem was approached through interdisciplinary research that combines systems analysis, technology assessment, field studies, and international benchmarking (including insights from South Korea's advanced food waste recycling system). Plastic contamination in bio waste is a systemic issue across the entire value chain. Kekkilä's operations were chosen as the point of intervention as it allows for the biggest immediate impact.

Based on research, a three-horizon progressive strategy was developed for reducing plastic contamination:

1. Short-term Strategy

This intervention would introduce depackaging technology at the composting facility. This solution could remove up to 98-99% of visible plastic contaminants from biowaste and can be immediately implemented. This short-term vision allows for a prompt and cost-effective way to restore product quality and reduce customer complaints.

2. Mid-term Strategy

This horizon suggests a transition towards data-driven automated waste processing. The depacker's operational data will be collected to for a collaboration initiative between a local technology focused university and Kekkilä. The goal is to develop an advanced depackaging process that would potentially combine computer vision and robotics and reduce the need for physically demanding labour cost effectively.

3. Long-term Strategy

In the future, the project aims to go beyond technologies and explore biological solutions. Plastic eating microorganisms offer the possibility to remove microplastics that technological systems can't remove. In collaboration with laboratories, these organisms and their efficiency will be tested before they are introduced into practice. The goal is to not only remove plastics from Kekkilä's products but also support ecological sustainability.

The proposed technology-driven strategy includes several steps towards plastic-free soil. However, the biowaste processing system is complex and is affected by many factors. The project discovered barriers to grocery store level separation that include time constraints, lack of resources, and unclear economic incentives. The international benchmarking in South Korea highlighted the importance of regulatory frameworks, financial incentives, and cultural practices in enabling better quality waste streams.

Overall, this project provides Kekkilä and other stakeholders with feasible recommendations, a clear strategic roadmap, and support for the future transition to cleaner biowaste systems. Our findings also reinforce the importance of collaboration between sectors, as meaningful progress requires co-operation from industry players, policymakers, and researchers. This long-term strategy enables gradually minimising the amount of plastic impurities in soil.

This report is not formal deliverables within the initial project plan, it directly contributes to the project's core strategic goals. By documenting and analysing plastic recycling and treatment processe, it serves as 'replicable practices', which was established as key objectives of the TREASoURcE project to ensure long-term impact and scalability.

# 1. Introduction

The collaboration with the Aalto University IDBM programme was designed to directly support the objectives of the TREASoURcE project by addressing challenges related to plastic recognition and biowaste sorting at the consumer level. By grounding the work in real operating conditions and live industry challenges, the project aimed to generate findings that are not only academically rigorous but immediately relevant for industry application and transferable to other European contexts. While the majority of biowaste is sourced from industry and retail, these solutions directly benefit consumers as end-users. By ensuring the precise removal of plastics from organic waste, the process yields safer, higher-quality soil products for consumer use.

Executing this task within an established and internationally recognised academic programme ensures the application of the latest research knowledge and methodologies. This is critical for ensuring the quality, credibility, and impact required by an EU-funded project. The defined challenge is connected to the target areas of TREASoURcE's WP2 (consumers and stakeholder engagement demos), WP3 (the circulation of non-recycled plastics), WP5 (biobased side and waste streams), and WP6 (transferable practices and exploitable results). In addition, WP8 (communication) disseminates the results to various stakeholders.

The participating company, Kekkilä, has contributed to the project primarily in the role of industry expert, challenge provider, and mentor for the student team, having backgrounds in business, design and engineering. Kekkilä has introduced real-world challenges based on its expertise in waste management and circular economy solutions. The company's role has been to ensure that the student work is grounded in practical relevance and reflects current industry needs, while keeping the focus on broader societal impact.

The selected student project focuses on the separation of plastics from biowaste. The challenge is highly relevant from a consumer perspective: by developing system-level improvements to separate plastics as accurately as possible, the project ensures that the resulting soil products are safer and of higher quality for consumer use. In this way, the work contributes to enabling better environmental outcomes and safer products for everyday life.

Plastic-free, high-quality compost supports healthier soils, cleaner food-growing environments, and reduced microplastic exposure for people and ecosystems alike, directly aligning with TREASoURcE's commitment to circular solutions that benefit both people and planet. Importantly, the results of this student project are public and openly available, ensuring that the knowledge generated can be widely utilised beyond the immediate project context. This openness reinforces the role of the TREASoURcE project as a driver of shared learning and scalable solutions, maximising its impact across sectors and regions.

### 1.2. Scope and Objectives

The project focused specifically on the Kekkilä composting facility located in Joutseno in the south-east Finland, which processes industrial biowaste. Municipal biowaste is not processed in the facility. The company's main source of impurities comes from Finnish grocery stores. Impurities refer to various-sized small plastic particles that have come from the degradation of plastic packagings. This is a critical scoping distinction: unlike household biowaste, grocery store biowaste arrives in a packaged biowaste format, meaning food and plastic packaging are not separated at the source before collection. This results in significant plastic contamination entering the composting process, which Kekkilä's current separation technologies are insufficient to address fully.

The project was structured around three evolving lines of inquiry:

1. The first was to map and evaluate existing plastic separation technologies, with particular attention to what is technically feasible at industrial scale and financially viable given the low-margin nature of compost products.
2. The second was an investigation of international solutions and practices. Rather than a broad benchmarking exercise, the team focused on identifying the most relevant innovations in Europe and in South Korea, a country recognised as a global leader in food waste recycling.
3. The third line of inquiry examined the upstream source of contamination: the grocery store supply chain. Since virtually all plastic impurities at Kekkilä Joutseno originate from packaged grocery store biowaste rather than consumer waste streams, the scope shifted toward understanding the structural and behavioural dynamics at the point of disposal in retail settings, and what interventions (whether technical, organisational, or behavioural) could reduce plastic contamination.

### 1.3. Key Stakeholders

The project mentors were Mihail Vinokurov for the Kekkilä side, Kaisa Sibelius for the Forum Virium Helsinki, and Ville Eloranta and Hanne Savolainen from the Aalto University. The student team consists of Alina Räkköläinen and Valerian Kaiser, who have backgrounds in business management; Anna Nurmi and Nelly Plukka, who specialize in chemical engineering; and Lucienne De Waal, who comes from the field of industrial design.

Regulatory stakeholders, including the European Union and national governments, set the compliance framework within which Kekkilä operates. The EU Fertilizer Regulation (EU) 2019/1009 (Regulation EU 2019/1009) is the most directly relevant instrument. It lays down rules for the placing fertiliser product on the market and the plastic impurity limits in fertilising products tightening from 5g/kg to 2.5g/kg in 2026. Furthermore, Finnish supermarkets are part of the challenge as their biowaste is being used for Kekkilä's final product.

## 2. Methods

The research methodology is based on the critical system thinking (CST). The CST is a multimethodological systems approach that aims to facilitate the understanding and addressing of complex challenges. The main objective is to help stakeholders notice weaknesses and development possibilities of the system. The theory includes four steps: explore, produce, intervene, and check. The explore step focuses on identifying the main issue and viewing it from systemic perspectives. The second step is to produce an intervention strategy based on systems approaches, models, and methodologies. The intervene step implements the chosen strategy and aims to reveal its possible weaknesses and opportunities. The final point is the check step that aims to evaluate progress, reflect results, and determine the next steps. The overall process highlights utilisation of a variety of systemic perspectives, methodologies, models, and methods. (Jackson, 2024)

The research was divided into background research and empirical research. The background research focused on understanding the challenge more deeply and the empirical research focused on a more in-depth analysis of the discovered opportunities, for example through a field trip. Therefore, both qualitative and quantitative methods were utilised during the research. The quantitative method focuses on, for example, analysing numerical data, testing hypothesis, and conducting statistical analysis. The qualitative method includes content analysis, interviews, and examines structured observations. By utilising both methods, it was possible to understand the problem holistically, but at the same time analyse the potential solutions statistically. (Erikson & Kovalainen, 2008)

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## 3. Background Research

### 3.1. The Problem: Plastic Contamination in Biowaste Composting

The composting process is a managed aerobic decomposition process in which microorganisms break down organic materials under controlled conditions of oxygen, moisture, temperature, and carbon-to-nitrogen balance, producing stable and nutrient-rich compost through active and curing phases (Chen et al., 2011). That process is complicated by the persistent presence of plastic contaminants, a challenge of structural rather than incidental nature. The waste produced by supermarkets is collected through designated packaged biowaste containers that accept food products in their original packaging. Workers disposing of expired or damaged goods under time pressure rarely remove wrapping before discarding. This means that plastic films, trays, bags, and other packaging materials enter the composting stream intact.

The consequences are twofold. First, visible plastic in the final compost and soil products generates customer complaints and damages brand reputation, which is Kekkilä's primary operational concern. Second, plastics that are shredded or fragmented during processing degrade into microplastics, that are particles with a size of 1-5 mm (Lopes et al., 2019). Microplastics persist in the compost, posing longer-term risks to soil health, microbial activity, and regulatory compliance (FAO, 2025). In particular, the Regulation (EU) 2019/1009 is reinforcing the urgency of finding effective separation solutions.

According to Kekkilä side mentor, Kekkilä's current plastic separation process includes on screening and wind separation. Their screener separates impurities from biowaste with 25mm screen. Pure biowaste goes through the screen and filters big parts of the impurities out. Their wind separator has a blower at the upscreen side and a suction system at the downscreen side, and the impurities are blown/sucked out based on different density compared to biowaste.

While functional at a basic level, screening and wind separation alone are insufficient to address the volume and variety of plastic contamination entering from packaged grocery store waste. This gap between current practice and required quality standards is the central challenge this project set out to address.

### 3.2. The Solution Space: Three Points of Intervention

Three distinct points were identified in the biowaste value chain where intervention is possible (see Figure 1). These are as follows: at the packaging production level, the plastic used in food packaging can be reduced or replaced. At the grocery store level, source separation can be improved before waste enters the composting stream. At the composting facility itself, in-process plastic removal can be enhanced. Each point of intervention carries different technical, economic, and behavioural implications, and no single approach is sufficient on its own. The following sections review the landscape of solutions available at each level.

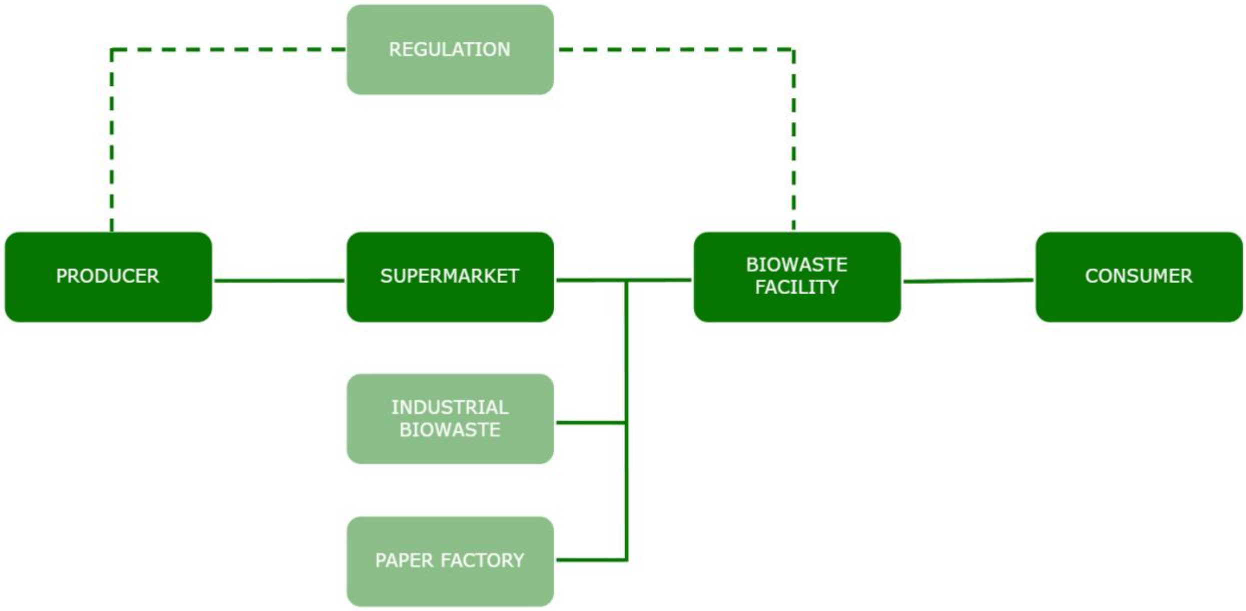


*Figure 1: Biowaste value chain (image by author)*

### 3.3. In-facility Separation Technology

The most direct response to contamination is to improve separation within the composting facility itself. Research into mechanical pre-treatment systems reveals significant variation in performance depending on the sequencing and type of equipment used. During the research, a few of the widely used potential technical systems, such as depackaging machines, pulper-based systems, and press-based systems, were examined. In addition, some high-technology solutions were evaluated.

Depackaging machines represent the most promising technology for facilities receiving packaged biowaste. These machines are specifically designed to open packaged food-waste and extract the organic fraction while keeping plastic packaging as intact and large as possible. This is critical because the sequencing of operations determines whether downstream separation remains feasible. Early shredding of waste irreversibly fragments plastics into small, flexible pieces that bypass screens and become embedded in the organic fraction. By contrast, a depackaging-first approach preserves separability, with studies showing plastic removal rates of up to 98–99% when combined with downstream screening. (Alessi et al., 2020; Lopes et al., 2019) For Kekkilä, whose primary complaint driver is visible plastic rather than microplastic content, this technology directly targets the most pressing quality issue.

Pulper-based systems offer even broader impurity removal, including glass and inert materials that screens cannot capture, and achieve near-complete plastic transfer to reject fractions (Alessi et al., 2020). However, they carry a significant trade-off, since approximately 20% of organic matter is lost to residues, reducing compost yield (Alessi et al., 2020). For a low-margin product like compost, this is a meaningful cost that must be weighed against quality gains.

Press-based systems, while simpler and less expensive, perform poorly at plastic separation, particularly when preceded by shredding, and are therefore not well suited as primary separation technology for packaged biowaste streams (Alessi et al., 2020; Lopes et al., 2019).

Beyond these mechanical approaches, some advanced sensors and artificial intelligence assisted sorting technologies were researched. They can offer for precision sorting and potentially valuable for quality monitoring. However, further research would have been needed to determine whether the technologies are applicable to wet and heterogeneous biowaste streams and the scale of the context. They are better understood as a future enhancement rather as an immediate stand-alone solution.

### 3.4. Source Separation

Addressing contamination upstream, at the point where waste is generated, is in principle the most efficient strategy, as it avoids the need for costly and imperfect downstream correction.

The manual removal of packaging from expired or damaged products is labour-intensive. According to Director of Finnish Grocery Trade Association, supermarkets choose to send their packaged biowaste to biowaste handling facility, since if they would do it at the supermarket site, it would require more space, labour and blades to be used, which causes occupational safety risk (I. Nieminen, personal communication, March 17, 2026). While Kekkilä charges lower gate fees for cleaner, pre-sorted waste streams, the cost savings do not reach a level that compensates supermarkets for the additional operational effort.

### 3.5. Biological Approaches: Plastic-Degrading Organisms

Alongside the mechanical and source-separation interventions described above, the team explored a longer-term biological approach: the use of plastic-degrading microorganisms to break down plastic residues, particularly microplastics, that mechanical systems cannot capture. This line of investigation was developed through interviews and consultations with researchers from Aalto University, including a former VTT scientist active in research on plastic biodegradation. These conversations confirmed that the field is scientifically compelling and rapidly advancing, but that the technology is currently at Technology Readiness Level 3 (TRL 3), meaning proof-of-concept has been demonstrated in laboratory conditions, but practical implementation at industrial composting scale has not yet been achieved. Encouragingly, many of the relevant organisms have been identified in natural environments, including compost piles and soil, indicating that biological plastic degradation is not an artificial process but an emerging pathway that nature has already begun to develop (Shah et al., 2008; Cowan et al., 2022).

#### 3.5.1. Mechanisms and Target Plastics

The three plastics of greatest relevance to Kekkilä's compost stream are polyethylene (PE), polypropylene (PP), and polyethylene terephthalate (PET). These differ fundamentally in how susceptible they are to biological degradation. PET contains oxygen atoms in its polymer backbone, making it hydrolysable by enzymes such as cutinases and PET hydrolases (Kawai et al., 2019). By contrast, PE and PP consist entirely of carbon-carbon bonds, which require high-energy oxidative enzymes such as laccases, peroxidases, and oxygenases to initiate degradation (Inderthal et al., 2021). PP is the most recalcitrant of the three due to the steric hindrance created by its methyl side chain (Arutchelvi et al., 2008). In all cases, a smaller plastic particle size (as found by Inderthal et al., 2021 with microplastics and sub-2 $cm^2$ fragments already present in composting streams) is actually advantageous, since the higher surface-area-to-volume ratio improves enzymatic access.

A selection of the most relevant organisms identified through the literature review can be found in Annex 1. This list includes: Ideonella sakaiensis, a bacterium isolated from a PET recycling site in Japan that uses dedicated PETase and MHETase enzymes to convert PET into non-toxic monomers (Yoshida et al., 2016); the engineered LCC-ICCG cutinase, which achieves over 90% PET depolymerisation in 10 hours at 65°C, a temperature that coincides directly with the thermophilic composting phase (Tournier et al., 2020); Brevibacillus borstelensis, a thermophilic bacterium active at 55–65°C that has demonstrated a 31% reduction in PE molecular weight within 30 days (Arutchelvi et al., 2008; Shah et al., 2008); and several white-rot fungi such as Trametes versicolor and Phanerochaete chrysosporium, which use laccase-mediator systems to oxidise PE and PP, and are naturally found in lignocellulosic compost environments (Fujisawa et al., 2001; Cowan et al., 2022). Many of these organisms, including common compost moulds such as Aspergillus and Penicillium species, are already present in mature compost without deliberate inoculation (Cowan et al., 2022; Arutchelvi et al., 2008).

### 3.5.2 Kekkilä's Operational Requirements

We have assessed potential biological solutions against a set of key criteria derived from Kekkilä's operational context. Any viable organism or enzyme system must satisfy the requirements that can be found in table 1.

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*Table 1: Criteria for biological solution selection*

| Criterium | Requirement |
|---|---|
| **Nutrient safety** | The organisms must not consume nutrients essential to compost quality (nitrogen, phosphorus, organic carbon from the biological fraction). |
| **Cost-effectiveness** | The approach must be economically viable for a low-margin compost product. |
| **Process efficiency** | Degradation must proceed at a rate sufficient to provide measurable benefit within the composting cycle. |
| **Temperature compatibility** | The temperature should be compatible with the current two-phase process of composting at the Kekkilä facility. |
| **Biosafety and containment** | Any organisms introduced must be either naturally occurring (already present in the environment at low levels) or neutralisable before the compost is released. The thermophilic phase itself provides a natural kill step for many mesophilic organisms. For engineered enzyme preparations, no viable cells are introduced. Deliberately inoculated novel strains would require regulatory assessment under EU frameworks before deployment. |

### 3.6. Rethinking Packaging

A longer-term structural solution lies at the packaging production level. If food packaging were made from materials that fully biodegrade under industrial composting conditions, the contamination problem would be resolved at source. Research into compostable packaging materials shows meaningful progress: studies conducted in French industrial composting plants found that certified compostable packaging breaks down with up to 98% degradation, leaving no detectable toxins, pathogens, or heavy metals in the final compost (Gastaldi et al., 2024). Projects such as HolyGrail 2030, a European industry initiative, are advancing digital watermarking of packaging to enable more precise automated sorting, representing a pragmatic near-term complement to longer-term material transitions. Some packaging producers are also incorporating enzyme-based additives that trigger degradation when packaging comes into contact with soil (Carbios, accessed 20.04.2026).

### 3.7. Synthesis: A Multi-level Problem

Across all lines of investigation, a consistent finding emerges: plastic contamination in composted biowaste is a systemic problem that cannot be resolved by any single technology or intervention. The three points of intervention, packaging, supermarket source separation, and in-facility processing, each address a different part of the same underlying dysfunction. Mechanical improvements at the facility, such as depackaging combined with screening, offer the most immediate and controllable path to quality improvement for Kekkilä. Upstream behavioural and regulatory interventions at the supermarket level address the root cause but require structural change beyond any single actor's control. Packaging level and biological solutions offer the most transformative long-term potential but are not ready for immediate implementation at an industrial scale yet.

This multi-level framing shapes the design concepts and final recommendations developed in the subsequent sections of this report.

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## 4. Empirical Research

Empirical research was conducted through expert interviews and field visit in Finland (Kekkilä's Joutseno facility), as well as in South Korea. South Korea was selected as a particularly relevant case due to its remarkable transformation in waste management over the past three decades.

The first field visit took place in January at Kekkilä's Joutseno facility. The aim was to gain a deeper understanding of the current biowaste handling process and to identify major challenges within the existing system. In February, a second field visit took place in Seoul. This visit focused on interviewing professionals from relevant sectors, gathering their perspectives on the problem, and exploring how South Korea increased its recycling rate from 2% to 98% (Ministry of Environment, 2025).

Semi-structured qualitative interviews were the primary data collection method. While each interview was designed around one of the identified points of intervention (at the producer level, at the source, or at the composting facility), all interviews shared the broader objective of developing a comprehensive understanding on how the problem could be addressed.

Interviewees were selected based on their expertise and relevance to the research topic. Some were chosen for their roles within the circular economy, with a particular interest in "paradigm-breaking" approaches beyond conventional industrial composting. Others were selected for their extensive experience in areas such as machinery, (grocery store) biowaste streams, logistics, production, separation processes, related operational systems, etc.

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## 5. Developing the Concept

When developing different visions for the possible solution for our project, we focused on the different points of implementation that can be seen in Figure 1. Considering the areas where the most effective contributions could be made, the proposed solutions focused on supermarkets and Kekkilä Joutseno site.

One of the visions that we had but eventually abandoned was an AI vision system (RGB and Hyperspectral cameras + deep learning) that identifies plastics on a conveyor belt. Then, the robotic arm with suction/gripper removes detected plastic, glass and cardboard fragments. A potential way of doing that in a similar field is AETech's Atron (AETech, accessed 29.04.2026). This machine exists already, but a lot of questions remained, for example if it would work for smaller plastic shreds and thin plastic films, which is relevant in this project context.

Throughout the project, a more traditional approach was also considered. The possible use of manual human sorting directly at the supermarkets was researched. Later on, this idea was disqualified by the team as it is costly for supermarkets and they do not have an incentive to do diligent sorting as a demand for packaged biowaste remains. Most importantly, this idea was thought to be unfitting because it relies solely on human labour. Moving forward with solutions that create a more sustainable, scalable, and humane system that reduces reliance on manual labourand improves working conditions was considered important.

Another direction we considered for the supermarket approach was whether it would be feasible to have different supermarkets bring their waste to a unified collection area. These regional depackaging stations would be near clusters of supermarkets, where a depacker separates the organic from the packaging material. Then, the clean biowaste is transported to composting or biogas facilities for further processing. The possible challenge with it would have been that it requires more collaboration between supermarkets, waste operators and treatment facilities and that supermarkets would have to pay for the depacker. In the end, we opted for implementing the depacker at Kekkilä's facility since it would be the most feasible and easily implementable solution.

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# 6. Results

## 6.1. The Strategy Towards Plastic-free Soil

The research conducted throughout this project converges on a clear conclusion: no single intervention is sufficient to resolve plastic contamination in composted biowaste. The problem spans multiple points in the value chain, involves stakeholders with misaligned incentives, and manifests at different scales simultaneously, from visible packaging fragments in bagged soil to small microplastic particles. Addressing it meaningfully requires a strategy that acts on multiple horizons.

The concept developed in this project is structured as a three-horizon roadmap, framed around the questions of what can be done in the short term, mid-term, and what this work can help build long-term. Each horizon builds on the previous one – together, they form a coherent pathway from immediate quality improvement to long-term ecological impact.

### 6.1.1 Short-term Strategy: Restoring Product Quality Through a Depacker

The biggest problem in Kekkilä's compost and soil products is the visible plastic, which leads to customer complaints and reputational risks. As mentioned earlier, research shows that installing a depacker at the Joutseno facility can reduce plastic contamination by up to 99% (Lopes et al., 2019). This is a proven, financially available solution for Kekkilä at this stage. The technology is rated at Technology Readiness Level 9, meaning it is ready for immediate implementation (Aalto University, 2025). It allows for a smooth transition stage at the facility as it does not require a change in supplier relationships or regulatory frameworks. The depacker allows Kekkilä control over its product quality in the near term and protects the downstream value of the composting and soil production process that sustains the facility's profitability.

There are several different depackers on the market with different operating principles and selling prices. In one example, packaged biowaste is fed into the machine via a screw conveyor. Inside the unit, a rotating shaft with paddles moves the material forward while applying force to the mass, which causes the packages to open. The system is designed to avoid shredding that would break packaging into small fragments. (Mavitec Green Energy, accessed 18.04.2026; Waste Food Solutions Ltd, accessed 18.04.2026).

As the waste is agitated and compressed, the released organic fraction is forced through a perforated screen surrounding the rotor. The screen openings allow food waste and other biodegradable material to pass through, while larger packaging materials remain inside the machine and continue toward the reject outlet. The packaging residue is then discharged separately for energy recovery. The packaging sidestream usually cannot be recycled due to it being contaminated with the compost material. (Mavitec Green Energy, accessed 18.04.2026; Waste Food Solutions Ltd, accessed 18.04.2026).

Kekkilä requires that the depackaging machine must be able to handle waste flow of at least 2000 tons annually. A potential machine that could be installed at the Kekkilä composting facility would require £55,000 (approximately 70 000 €) initial investment (Waste Food Solutions Ltd, accessed 18.04.2026). A rough estimate for total cost of ownership is calculated with the following formula (Soontact, accessed 20.04.2026):

**Total cost of ownership = Initial Cost + Installation + Training + Maintenance + Energy + Spare Parts + Repairs − Residual Value**

Results of our calculations for daily total cost of ownership and the roughly estimated annual maintenance costs are performed in table 2.

*Table 2: Rough estimate for total cost of ownership for a depackaging machine (Soontact, accessed 20.04.2026).*

| Cost component | Repetition | Total (€) during full life cycle (estimated 10 years) |
| --- | --- | --- |
| **Initial investment** | Fixed | 70 000 |
| **Installation** | One-time | 7 000 |
| **Training** | One-time | 2 000 |
| **Maintenance** | Annual | 50 000 |
| **Energy** | Annual | 25 000 |
| **Spare parts** | Annual | 15 000 |
| **Repair costs** | Annual | 10 000 |
| **Total cost of ownership** | | 179 000 |

It is important to note that the results from this calculation can vary a lot in practice since all the total prices in column ''**Total (€) during full life cycle (estimated 10 years)**'' have been estimated based on Soontact's average percentages and the results must be therefore taken just as a rough estimate.

Considering the investment and potential benefit for Kekkilä's final product, depackaging machine can offer a direct solution to reduce plastic in soil and plastic accumulation in nature and is the reason why we chose it as one part of solution.

#### 6.1.2 Mid-term Strategy: Improving Process Through Data and Automation

The depackaging machine is great at separating plastics from packaged food waste but the context-appropriate machine alternatives require human supervision and assistance (Soontact, accessed 20.04.2026). Working in biowaste handling is physically demanding and monotonous work and strong odours in biowaste provide an unpleasant working environment (Poole & Basu, 2017). Human intensive labour is also difficult to scale long-term. As a mid-term objective, the concept envisions reducing reliance on manual labour by using operational data to optimise and eventually automate the depackaging process cost effectively. The employees assisting the depacking machine have an important role in ensuring that the next, upgraded machine implemented at the facility can operate independently. When operating current depackaging machine, employees will simultaneously collect data on which packages require manual assistance to pass through the machine and what other bottlenecks the machine faces that require human intervention. Collecting data would be integrated into the company's current quality controlling and process development practices. Kekkilä's operations are based on constant development in environmental sustainability, safety and quality, so the aim of this strategy is to support the development of the operation (Kekkilä-BVB, accessed 17.04.2026). Implementing the data model presented in the table 3 must be further refined and complete in the company's process environment.

*Table 3. The model of the machine operation documentation practices in context.*

| Collected data | Impact on process | Instruction | Frequency |
|---|---|---|---|
| **Operators input** | Impacts on efficiency | Define in which situations and when it is needed | Periodically |
| **The quality of input compost** | Impacts on the separation results | Monitor the overall quality of compost, and the quantity and types of food packings | Continually |
| **The quality of output compost** | Impacts on the customer complaints | Monitor the overall quality of compost and possible impurities and their total amount | Continually |
| **Machine breakdown** | Cause production downtime | Ensure that all breakdowns and their root causes are documented | Continually |
| **Machine maintenance** | Cause production downtime | Document all maintenance tasks | Continually |

The collected data will be used to fuel a collaboration initiative with a local technical university and Kekkilä (see figure 2). With the help of the data, both parties will collaborate to create a cost-effective, upgraded depackaging machine. The development project can focus on improving an existing machine or designing an entirely new machine depending on the quality of the obtained

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data, the company's current plans, and other possible factors. The project would potentially combine computer vision to recognize plastics that can’t pass through the machine without human intervention and robotic arms to remove them from the stream and separate them. The use of computer vision and robotic arms in separation processes have been validated in relevant environments, placing this at Technology Readiness Level 5 (Aalto University, 2025). The goal is that through data-driven improvements, a fully automated process will result in low impurity products for Kekkilä without requiring employees to physically handle contaminated waste streams. In addition, the new depacker would ideally be able to produce sorted side stream flow due computer vision sorting or other technology, which would enable valuable packaging materials to be recycled afterwards. In terms of circular economy, the collection and recycling of the side stream is also an important part of the process.


*Figure 2. A collocation initiative with the participating company and a local technical university (image by author)*

### 6.1.3 Long-term Strategy: Breaking the Cycle of Downcycling Through Plastic-eating Organisms

Microplastics below the threshold of mechanical detection that remain in the compost and pass into the soil are a constant threat. These represent both a long-term regulatory risk, as EU standards are expected to continue tightening, and a genuine environmental concern, as microplastics in agricultural soil affect microbial communities, plant uptake, and ultimately the food chain and human health. The long-term vision of this project is the introduction of plastic-degrading biological species. Specific fungi and bacteria are added directly into the composting process known to enzymatically break down common food packaging polymers including polyethylene (PE), polypropylene (PP), and polyethylene terephthalate (PET). This would address what mechanical systems fundamentally cannot: the residual microplastic fraction. It would also position Kekkilä as a pioneer in a field that is rapidly advancing scientifically and help the company proactively meet future soil quality standards for agricultural use. Crucially, achieving this vision requires beginning the groundwork now, which is why this project includes a proposed roadmap of next steps to support the transition from current research (Technology Readiness Level 3) towards eventual implementation.

### 6.2 Proposed Pathway Towards Implementation

The implementation process will complement the depackaging machine once it is fully developed and after an initial testing phase, might even replace the machine entirely. The estimated timeline for this project is 5-15 years as it requires extensive testing of the usability of bacteria and algae for Kekkilä's purposes and actual introduction into the facilities will need permits from entities such as Finnish Food Authority or Finnish Safety and Chemicals Agency (Tukes). A short overview of the activities can be found in the table at the end of this chapter.

As a first step, Kekkilä will look at securing a strategic partnership with a laboratory in order to test the efficacy of the plastic-eating organisms for their own samples. From our talks with researcher from the Chemistry Institute at Aalto University, we know that they are currently in the process of building a biodegradation lab. Since the full functionality will only be next year, it will have some functionality later this summer so that could be an option to continue the partnership in the future. Contacting local universities for a potential interest in the project could also prove to be a viable option due to its proximity to the Kekkilä facility. The proper evaluation of what can be achieved, and further definition of the implementation will be done in the period of May until August. Regardless, plastic-eating species should target PE, PP and PET materials and not consume too much of the biowaste material.

Depending on the speed of finding an agreement with a laboratory, field samples can already be taken during that same period in summer. This will also help in correctly identifying the percentages of different plastics in the biowaste, which, in turn, ensures that the correct organisms are being selected to degrade the plastic waste.

Now that those plastics have been identified, Finnish Food Authority and Tukes should be contacted in order to discuss potential extra safety tests and requirements for the plastic-eating organisms. According to Finnish law, this project falls under the Fertilizer Act (711/2022) and Ministry Decree (964/2023). Then there are also public concerns that have to be taken into account:

- Landscaping Compliance Audit: Verify soil against Decree 964/2023 standards for "Substrates" (Kasvualustat).
- Urban Environmental Impact Study: Specifically assess risks to urban groundwater and non-target soil organisms (pollinators/earthworms) in public settings.
- Tukes "Material Integrity" Review: Does the consortium need to be deactivated before being released to the public in order to prevent any risk of degrading urban plastic infrastructure (pipes/cables)

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*Table 4. Simplified phases for the implementation at Kekkilä's facility.*

| Phase | Further explanation |
|---|---|
| **Partnership Phase** | Infrastructure audit & securing of partnership with laboratories |
| **Field Work Phase** | Comprehensive sampling of plastic concentration levels |
| **Biological R&D Phase** | Consortium testing of degradation potential amongst different plastic-eating organisms |
| **Regulatory Phase** | Early engagement with authorities and cross-checking for |
| **Safety & Testing Phase** | Validating deactivation of organisms in different temperatures |
| **Review of Organisms** | Go/No-Go decision point |
| **Regulatory Check** | Engagement with authorities on introduction of product |
| **Pilot Phase** | Logistical acquirement of organisms and introduction in Kekkilä facility |

Kekkilä can conduct extra tests and try out modifications/other versions of the organisms while Tukes and Finnish Food Authority conduct analyses of the organisms. This can be simultaneous to deactivation testing – some organisms may thrive in low temperatures but deactivate at 60°C, whilst it might be exactly the other way around for other organisms. Depending on the feedback of the authorities, this presents a crucial point in the process. The difference between going from the deployment phase back to the development phase is essential in defining the process duration, and therefore it is important to know in which phase Kekkilä is. Since some problems are very likely to pop up during the evaluation process, the switch between the phases may occur quite often.

Taken together, these three horizons represent a strategy that is grounded in what is currently operationally feasible, clear about what direction the technology needs to take, and ambitious about the kind of legacy that a composting company, and the circular economy more broadly, can leave for the health of people and planet.

## 7. Consumers' Connection to the Challenge

There are careful sorting instructions available for citizens on how to dispose of the biowaste they produce in their homes. As a large part of the biowaste that Kekkilä receives comes from grocery stores, the quality of the biowaste produced by consumers in domestic environments is not relevant for the scope of this project. However, consumers do relate to the research through consumption behaviour and role in the circulation of the food chain.

During the project it became evident that the root cause of our problem – packaged biowaste – is largely the consequence of the current food consumption model. Consumers are accustomed to a world of abundance and when shopping for food, a large variety and availability of products is expected at all times. This consumption model inevitably leads to overstock which then ends up as packaged biowaste.

In an interview, Director of Finnish Grocery Trade Association, stated that under the current model grocery stores do not have the capacity and resources to separate biowaste from packaging at store level (I. Nieminen, personal communication, March 17, 2026).

As discussed, expired food products end up in biowaste in grocery stores in their original packages. Shifting this work stage to grocery stores would significantly increase their operational costs, which would, in turn, raise food prices and directly affect consumers. In addition, the grocery stores utilise, for example, evening sales to decrease the amount of direct food waste as consumers can buy food products that expire soon at lower prices (S-ryhmä, accessed 06.04.2026).

When the soil used to produce foods contains plastics, it can transfer to products that consumers are consuming for nutrition (FAO, 2025). Therefore, consumers benefit from our strategies to remove plastics in soil as those can lead to healthier food.

## 8. Conclusion and Next Steps

The goal of this project was to find cost-effective approaches to remove plastic contamination from biowaste at an industrial scale. Through extensive research in the field of biowaste management and existing technologies, it became evident that interventions in regulations, packaging, and at grocery stores are essential. The most controllable leverage point for the participating company, Kekkilä, is within their own operations and this is what the developed strategy targets.

A threefold strategy for removing plastics from biowaste was introduced in this report. It combines immediate adoption of the current state of the art technology – the depackaging machine, developing that technology into an autonomous process with the help of data as well as the introduction of organisms to remove microplastics. Our findings support the need for collaboration between multiple sectors as no single actor can solve this challenge alone.

Based on our research findings the following steps are recommended:

1. Short term: Evaluate and implement the most suitable depackaging solution, while monitoring its impact on plastic removal and operational bottlenecks.
2. Mid-term: Use collected data in collaboration with universities to develop smarter depackaging technology, such as computer vision and robotics, to improve efficiency and reduce manual work.
3. Long term: Advance innovation through research on enzymatic microplastic removal and microbial optimization to further improve compost and soil quality.

Through combining immediate action, continuous improvement and the long-term vision, Kekkilä can offer higher quality products for customers and contribute to creating healthier soils. Alongside the proposed technology-driven strategy, it is worth highlighting significant factors that will directly and indirectly influence further development and, more broadly, the future of the system.

Legislation has a great impact on the development of the system based on this study. Packaging and Packaging Waste Regulation (PPWR) is one of the current essential changes in the European Union's legislation regarding recycling and circular economy. The regulation focuses on increasing recycling of packaging, and the aim is to make every packaging recyclable by 2030 and increase the share of recycled materials in new packaging materials (PPWR, 40/2025). There are several laws regarding waste treatment in addition to this regulation, but our results generally emphasised that legislation can effectively influence stakeholders and various impacts concerning the future development of the challenge.

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Although Kekkilä does not receive biowaste from consumers in this context, it has an impact within the whole biowaste system. Individual engagement has been researched to support generally implementing the change in the system. In the future, it will continue to be significant to support urban recycling plans, which offer recycling guidelines to companies and households. Collecting biowaste offers raw materials for Kekkilä, as well as benefits for both nature and society, and therefore the further dissemination of information regarding methods of implementing biowaste recycling is essential.

This study utilised interdisciplinary expertise in chemical engineering, business, and industrial design. During the project, the research team gained knowledge about biowaste management in Finland, as well as, at an international scale especially in the context of South Korea. One of the key learnings was understanding the sometimes-conflicting goals and impacts of different stakeholders, as well as system boundaries. Assessing and challenging system boundaries facilitates, for example, a better understanding of values, power structures, and other relevant information (Ulrich & Reynolds, 2020). Methodological approaches, including qualitative and quantitative methods, helped in gaining a deeper understanding of the biowaste processing system and identifying bottlenecks and potential opportunities to develop the system.

As a final point, the proposed strategy was presented successfully to the mentors. The participating company showed interest in the strategy and started to plan the possible machine investment. In addition, they are eager to hear more about the possibilities of utilising microbes to break down plastic in the soil. The final strategy towards pure and high-quality soil supports the participating company to maintain and increase customer satisfaction. At the same time, it has a positive impact on the accumulation of plastic pollution in soil and nature over time. The long-term strategy enables gradually minimising the amount of plastic impurities in soil.

TREASoURcE

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## ANNEX 1 – Benchmarking Plastic Eating Organisms

| Organism / Enzyme | Type | Target Plastic(s) | Key Enzyme(s) | Optimal Temperature | Documented Degradation Speed | Suitability for Compost | Source |
|---|---|---|---|---|---|---|---|
| **Ideonella sakaiensis 201-F6** | Bacterium | PET | PETase + MHETase | 30–37°C | PET film (60 mg) ~100% degraded in 6 weeks; rate 0.13 mg $cm^{-2}$ $day^{-1}$ | Mesophilic phase; naturally present near plastic waste sites; whole-organism inoculation | Yoshida et al. (2016) |
| **LCC-ICCG (engineered cutinase)** | Enzyme prep. | PET | Cutinase (LCC variant) | 65°C (Tm 84.7°C) | >90% depolymerisation in 10 h; 16.7 g TPA $l^{-1}$ $h^{-1}$ | Best match for thermophilic composting phase; dose as enzyme prep during hot phase; highest performance known | Tournier et al. (2020) |
| **Thermobifida fusca / T. cellulosilytica (cutinases)** | Bacterium | PET | BTA hydrolases (TfH) | 55–65°C (thermostable with $Ca^{2+}$) | 40–50% PET film hydrolysis in 3 weeks at 55°C | Thermophilic composting phase; naturally abundant actinomycetes in compost | Kawai et al. (2019) |
| **Fusarium solani / F. oxysporum** | Fungi | PET | Cutinase (FsC) | 25–35°C | Lower activity than LCC (88× slower than PETase); some growth on PET mineral medium | Naturally present in compost soils; useful background degradation at mesophilic phase | Yoshida et al. (2016) |

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| **Rhodococcus ruber C208** | Bacterium | PE (LDPE, HDPE) | Laccase (bacterial, copper-inducible) | 30–37°C (laccase active 30–60°C) | 8% gravimetric weight loss in 4 weeks (photo-oxidised PE); Mw reduced 20%, Mn 15% by purified laccase | Strong biofilm on PE; mesophilic phase; copper availability in compost enhances activity | Santo et al. (2013); Arutchelvi et al. (2008) |
| **Brevibacillus borstelensis** | Bacterium (thermophile) | PE (LDPE) | Oxidases (not fully characterised) | 55–65°C | 31% Mw reduction; 11% mass loss in 30 days (UV-irradiated PE) | Excellent fit for thermophilic composting phase; outperforms R. ruber in speed | Arutchelvi et al. (2008); Shah et al. (2008) |
| **Trametes versicolor** | White-rot fungus | PE, Nylon | Laccase + HBT mediator (LMS) | 25–37°C | Mw reduced from 242,000 to 28,300 in 3 days (LMS treatment) | Natural lignin mediators in compost may substitute HBT; mesophilic phase; highly promising | Fujisawa et al. (2001); Cowan et al. (2022) |
| **Phanerochaete chrysosporium** | White-rot fungus | PE, PP (pre-treated) | LiP, MnP, Laccase | 37–45°C | Faster $CO_2$ evolution and elongation reduction vs. uninoculated controls in soil; >40% weight loss reported in some studies over 15–90 days | Ideal for lignocellulosic compost matrix; produces all three key ligninolytic enzymes; naturally abundant | Arutchelvi et al. (2008); Cowan et al. (2022) |
| **Bjerkandera adusta** | White-rot fungus | PE (HDPE, LDPE) | MnP, Laccase | 25–37°C | Enhanced HDPE degradation vs. control when lignocellulose co-substrate present; detailed rate data not specified in cited studies | Co-metabolic enhancement expected in organic compost; good candidate for inoculation | Cowan et al. (2022) |

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|---|---|---|---|---|---|---|---|
| **Aspergillus flavus / A. niger** | Fungi | PE (HDPE, LDPE) | Laccase-like MCOs (multicopper oxidases) | 25–37°C | Significant Mw and Mn reduction of HDPE over 28 days (A. flavus); carbonyl formation and amorphosity reduction confirmed for A. niger | Common compost moulds; will proliferate without inoculation; useful background PE oxidation | Cowan et al. (2022); Arutchelvi et al. (2008) |
| **Penicillium simplicissimum / P. pinophilum** | Fungi | PE, PP (pre-treated) | CYP450 hydroxylase; β-oxidation pathway | 25–30°C | 31.5% weight loss (P. simplicissimum); 3.26% mineralisation of pre-treated PP in 9 months; confirmed C–C bond cleavage by HT-GPC and FTIR | Ubiquitous in compost; mesophilic phase; requires UV/thermal pre-treatment for PP; naturally present | Arutchelvi et al. (2008); Cowan et al. (2022) |
| **Pseudomonas chlororaphis, P. stutzeri + Vibrio sp.** | Bacterial consortium | PP (isotactic, untreated) | Alkane hydroxylases | 25–35°C | Hydrocarbon degradation products confirmed by GC-MS, FTIR, NMR; quantitative rate data not available in cited literature | Only consortium documented for untreated PP degradation; Pseudomonas spp. are naturally present in compost environments | Arutchelvi et al. (2008) |
| **Cladosporium cladosporoides + R. rhodochrous + Nocardia asteroides** | Mixed fungal-bacterial | PE (HDPE, LDPE) | Oxidases (unspecified); laccase (R. rhodochrous) | 25–30°C | 60% mineralisation of degradable PE in 6 months | Natural soil/compost community members; useful for background PE | Arutchelvi et al. (2008) |

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| | | | | | | mineralisation in longer composting cycles | |