UKRI PROJECT – 10020315, COMPOSTABLE COALITION– WORK PACKAGE FOUR – COMPOST TESTING AND ANALYSIS. DEGRADATION TRIALS.

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AUTHOR NOTE

Completed as part of the UKRI project 10020315 - Compostable Coalition UK project looking at the degradability of compostable packaging and non-packaging, which are intended to be marketed as organically recyclable through industrial composting. This report is to provide the results, information, and informed opinions of experts within the relevant fields for Work Package 4 of the project. Methodologies, processes, and procedures can be found in the proposal documentation.

Thanks to the following members of the Compostable Coalition UK for organising the trial materials:

Abstract

Envar Composting Limited has designed and undertaken a suite of operational experiments and collected data to better understand the degradation profile of intermediate materials and finished products certified as "compostable" under one of the independent certification bodies' certification schemes. Most of the materials and finished products supplied were finished packaging products and intermediate materials (polymer films) used for making packaging products, while at least one product supplied was a format not classed as packaging. To ease readability, this report refers to these intermediate materials and finished products as 'compostable packaging' where talking about them collectively.

The main trial and data collection took place over a period of three months, beginning in late December 2022. The bespoke testing apparatus Envar Composting Ltd owns (Envar Composting Ltd Mini Composter) continues after the period mentioned above for the main trial. The data from the Mini Composter trials shall be made available when all tests are completed, which is anticipated to be prior to the completion of the UKRI project 10020315.

The material provided data which shows that compostable packaging does break down in an industrial composting setting with a steady degradation profile over time. The degradation profile is affected by how the material is managed and the extent it is spread throughout the composting mass. Despite some of the materials remaining visible at the final stage of the composting process, it was found that contamination levels of the final compost as per the industry standard tests showed the screened compost was compliant with quality requirements set in PAS100. Analysis looking at all types of microplastics also showed that compostable material microplastics were not present in sampled, screened compost, indicating a full breakdown.

The analysis concluded that through the operational control of the composting process, compostable materials independently certified compliant with standards (EN 13432, EN 14995 or ASTM D6400) are compatible with the desired environmental outcomes of our society.

Contents

Background

Soil Health

Soil health is defined as the continued capacity of soil to function as a vital living ecosystem that sustains plants, animals, and humans. Soil is an important natural capital resource. It provides us with many essential services. Soil biodiversity and the many biological processes and soil functions that it supports are thought to be under threat. In England and Wales: almost four million hectares of soil are at risk of compaction, over two million hectares of soil are at risk of erosion, intensive agriculture has caused arable soils to lose about 40% to 60% of their organic carbon. Soil degradation was calculated in 2010 to cost £1.2 billion every year. Compaction and the loss of organic carbon are serious threats to soil health. They affect agricultural production and our resilience to climate change. UK soils currently store about ten billion tonnes of carbon. This is equal to 80 years of annual UK greenhouse gas emissions, waste food and growing crops for bioenergy. All of which are putting additional pressure on soils. The importance of soil quality is without question a huge factor for the future. Soil improvers could not be more important in present time; this problem will only get worse unless we do something about it.

Adding organic matter back to the soil in the form of composted bio-waste assists in remedying the above stated issue. In turn re-building the soils structure, adding water retention and drainage properties, relieving compaction, and enhancing microbial biodiversity.

Compost in Agriculture

Historical Use

Composted bio-waste, that meets End of Waste criteria (certified by REAL's Compost Certification Scheme as compliant with PAS100 and the Compost Quality Protocol) or is assessed and authorised by the environment protection regulator for spreading to land, is a stable, safe, and easy way to manage renewable resource. Bio-based fertilisers and soil improvers have been the backbone of traditional farming for centuries. Animal manures, mushroom composts, paper crumb and other organic materials have been sought after and used in most types of farming; whether stockpiled and directly applied mechanically or applied through periodic grazing.

Safety

The compost has passed a set of tests required by the PAS100 standard to enable certification. The manufacture of the material is as per the PAS's requirements and those in the Environment Agency, Natural Resources Wales and Northern Ireland Environment Agency supported Compost Quality Protocol, and the Renewable Energy Assurance Ltd.'s Compost Certification Scheme Rules. The material is a source of the three major plant nutrients N, P and K (nitrogen, phosphorous and potassium) as well as having beneficial properties for the rest of the soil which are not found in manufactured mineral/ dissolvable granulated fertilisers, e.g., organic matter, secondary nutrients and trace elements that support plant nutrition and beneficial microbial species. Compost's organic matter content – the amount and complexities of the carbon-included molecules it contains – affect mobility of nutrients in the compost, most of its nutrient content becoming available to plants more slowly than from traditional, dissolvable granulated fertilisers. There are benefits from adding a slow-release nutrient capacity to the soil rather than a large addition of manufactured material at a single point in time which is subject to migration and potential pollution.

The risk posed by the compostable packaging is considered in this report and weighed against the realised and evidenced dis-benefit of using manufactured fertilisers.

Using composts and adding other sources of organic matter to the soil promotes the natural degradation processes and microbial communities, which are found in more natural and undisturbed soil, for example one which may be found in woodland or in natural heathland. This soil will contain more lignin, hemi-cellulosic and cellulosic molecules (examples of molecule types that are part of 'organic matter') which are not fully degraded but are in the process of undergoing degradation over time (rates depend on molecule types and conditions within the soil) with slow acting fungi and Psychrophilic bacteria. These slow acting fungi and Psychrophilic bacteria are active at lower temperatures than what is found in industrial composting active phases. The fact a waste derived compost is not completely mineralised at the point of use is not considered a safety risk; indeed, its organic matter content is a beneficial feature because it contributes to the natural carbon cycle found in normal, natural systems and enables the dynamic interactions between soil and plants that are influenced by weather conditions and other factors.

Industrial Composting of Waste Biomaterials

Traditional Plastics Problem

Composting of green waste and food waste breaks down organic matter. The material is degraded through mechanical, chemical, microbial, and thermal modes in this managed natural process. The most widespread problem all composters face in the industry is the contamination of feedstocks by traditional (non-compostable) plastics. This is because the modes of degradation in composting do not affect traditional plastics beneficially or at all, and in certain circumstances the contaminating traditional plastic becomes worse under treatment.

Processes of Breakdown

For background, below the processes of breakdown of composting materials in industrial/ commercial scale composting has been described. This is not supposed nor intended to be an academic review of breakdown processes, rather it gives a lay understanding in the context of breakdown when material is processed through our composting operations.

Mechanical

Mechanical breaking up of material is undertaken in the form of shredding the homogenised feedstock through a slow speed shredder. This happens prior to the composting of materials, whether the composting process is in vessel or open windrow. The purpose of this is to reduce the size of large items, increase the materials' surface area to volume ratio and to homogenise the materials. High nitrogen and high carbon materials are blended as best as possible helping to ensure effective breakdown via microbial and thermal modes of degradation during the later stages of the composting process.

The mechanical process also serves to liberate materials from each other, for example a sack containing cut grass. The sack would be required to be removed to enable its contents to be effectively mixed and composted. The mechanical process would serve this purpose. However, this action; when traditional plastics are used as the container, causes the liberated plastic to be more difficult to be collected as part of the quality control process, as it is smaller after being shredded. However, it is essential to the process to liberate the material. Hand removal at the front end of the composting process in a commercial/ industrial setting is not practical due to the sheer volume of materials being managed and processed at site. The small plastic pieces cause environmental problems which an operator is expected to control. Issues include the windblow of plastic and the requirement to capture it (so it does not blow off site), its removal from the composting mass and the cost of disposal after the removal. Costs are required to be passed onto the customers (waste suppliers) who are often local authorities.

Microbial

Microbial action is responsible for the thermal degradation as a secondary effect of the metabolic processes of the microbes which are inherent in the waste materials. Microbes release various enzymes and absorb nutrients from the degrading material. This is known as extracellular digestion, combining them with oxygen from the air in respiration - Respiration is a biologically active process; this means that release of carbon (respiration) by microbes coincides with the uptake of carbon and nutrients (microbial assimilation). This is why we call composting an aerobic process, microbes include bacteria and fungi and there is a wide variety of species which undertake degradation. Some of the more well-known species are Actinomyces, which is the light grey fungi-like bacteria that form spider-web-like filaments under the surface layer of the compost.

During decomposition the organic molecules in organic matter are broken down into simpler compounds which require further decomposition or into mineralised nutrients. The compounds in organic matter vary in the ease with which microorganisms can break them down. The first organic compounds to be broken down include amino acids and sugars. Cellulose will break down more slowly and lignin, phenols and waxes will degrade over a longer period. It is worth noting that the degradation of the later listed more complex materials is slower, which means they may not be completely broken down by the time the material is considered “stable” by the relevant product standard, e.g. PAS100. This is acceptable and beneficial to the soil carbon cycle, see the section on safety.

Figure 1 - Actinomyces in compost.

Chemical

Chemical reactions aid in the breakdown of composting materials. When the degrading matter breaks down it releases nutrients which are dissolved by water and removed in the leachate. Hydrolysis reactions also occur within the degrading mass where a water molecule breaks one or more chemical bonds in the degrading material. This often actually releases further water molecules from the macrostructure and, coupled with the increased temperature, hydrolysis is a key part of the degradation of biological materials and compostable plastics. For example, Polylactic acid has a backbone of $(C_3H_4O_2)_N$. The addition of H_2O hydrolyses this to $C_3H_6O_3$ – Lactic Acid. Oxidation then converts lactic acid into carbon dioxide and water through metabolic oxidation.

Water is also absorbed into natural fibres such as cardboard, paper, and compostable fibre-based items where it weakens the bonds between the fibres by pushing them apart and allowing for further mechanical or microbial action through a larger surface area.

Thermal

Degradation speed is affected by the energy in the material available for the microbes to use and therefore is related to the thermal output of the material. When microorganisms metabolise, they use oxygen to create energy in normal cellular respiration and growth. In a composting pile this heat is retained as the pile is self-insulating. The pile self-insulates as a function of its large size and low surface area to volume ratio. Temperatures during the most active phases of the composting process regularly sit at 60-80 degrees Celsius. Thermal degradation is a complex phenomenon leading to the appearance of different compounds, e.g. increased temperature also increases the rate of hydrolysis of the material. Oxidation of the carbon element of compostable plastics and other biodegradable complexes in the products is increased in speed through the available thermal energy derived from microbial processes.

Degradation Trials

Industrial Composting Trials

Method Brief

The full methodology is laid out in the proposal documentation for this project. Here, in this report, is a brief methodology description to explain how the process was run as practical implications were realised, which led to the originally planned methodology being slightly adapted to ensure the trials were achievable in practice.

- Materials (samples of compostable intermediate materials and finished products tested for the trial – see table 1 below) were pre-collected and kept secure in the waste transfer building before being incorporated with food and garden waste, during on-site waste pre-treatment, on a set date. The different materials (due to the nature of delivery/ different formats materials were received in) were added differently.
- The materials were all (apart from products SAMPLE 8 and SAMPLE 6) unused and un-soiled with food. Materials which were packaged in non-compostable packaging were removed from that packaging before being incorporated into the infeed biowastes (largely food and garden wastes), which had been selected and segregated for the trial.
- The block baled materials received to site were released from the block ties and were shredded separately. This was to break the block bales up prior to incorporating into the pre-shred mass of food and garden waste. All materials together were then shredded to ensure the trial was as close to normal waste pre-treatment as possible.
- The compostable materials, food and garden wastes were blended mechanically using loading shovels before being shredded.
- Samples of each compostable material provided by the project partners was placed into their own individual net bag for the recovery degradation analysis. These samples were not subject to the pre-treatment process of shredding before being inserted into the composting start-batch.

Once the material had been shredded and loaded into the tunnel system (the in-vessel, first biological phase of the composting process), the net bags containing the sub samples of individual materials were placed into the composting mass at least two inches below the composting batch surface and marked by pegs attached to the bags by rope.

Inputs & Process Details

Please see Table 1 noted below, for the Input material data, noting type of product and total weight of material received for use in the project trial. A brief description, see Observed Input Material Information, has been given for each material providing observations to its properties as they apply to the composting process, including any risks which the material may present to the quality of output or the compliance of the operation with its waste management permit.

Materials that came in for the purpose of this trial were not necessarily in the expected format of receipt to what would be normally delivered to site post-consumer use. The formats received for the trial were loose, compressed, and baled materials. The format of the material received was found to have an impact on the level of degradation. This has been discussed in more detail later in the report.

Table 1 - Details of materials used in degradation trial, their sub-total weights, and their collective total weight.

Product Code	Product		Weight (kg)
Sample 1	Dry - Bags	Loose	1125.00
Sample 2	Dry - Bags	Loose	2000.00
Sample 3	Dry - Bags	Loose	80.00
Sample 4	Tea bags	Loose	67.00
Sample 5	Unused coffee pods	Loose	145.00
Sample 6	Used Coffee Pods	Loose	66.00
Sample 7	Dry - Compound	Loose	589.00
Sample 8	Used Compostables – tableware	Semi-compressed	5980.00
Sample 9	Film used in sweet wrappers	Baled and compressed	3000.00
Comingled Food & Green	Normal incoming feedstock		159,960.00
	Total Weight (kg) Packaging		**13,052.00**
	Total All		**173,012.00**

Observed Input Material Information

- SAMPLE 1 Bags: 80-micron bags. Thick in nature and robust. Arrived loose and blended easily with other materials.

- SAMPLE 2 bags: 40-micron bags. These were the same as the SAMPLE 1 bags except for their thickness and blended easily. The large paper-type board label on them was incorporated also.

- SAMPLE 3 caddy liners/carrier bags: The caddy liners were 14 microns, and the carrier bags were 19 microns. These bags we experience as part of our normal composting processes outside of this trial. They are stretchy in composition and green in colour. As they were unused, they arrived in long rolls and unopened/unfilled, which would not be as per usual 'wastes received' in an industrial setting. Shredded and incorporated well.

- SAMPLE 4 tea bags: these bags were shredded and incorporated into the material, spreading easily. They were dry, which is not how they would be expected to be delivered in the case of normal use. Under expected used conditions the tea bags would already be undergoing degradation on arrival due to being exposed to heat and water in their product use phase, then being put into the relevant waste disposal bin to be collected kerbside for an expected minimum of 72 hours before delivery. The tea bags split readily as they were incorporated during the pre-treatment phase.

- SAMPLE 5 Un-used Coffee Pods: the coffee pods were left in the boxes and run over with the 18-tonne loading shovel to de-package before being shred into the process. The pods broke apart into fragments and were incorporated easily. Most of the pods were broken and all the coffee granules were spread into the material. The coffee pod material was heavy and thick and did not seem like it would easily become windblown.

- SAMPLE 6 Used Coffee Pods: these used coffee pods were de-packaged using the same process as the SAMPLE 5 material. Materials would be shredded so in reality there would be very little difference in the mode of presentation and any effect on the outcome of degradation.

- SAMPLE 7 compound: this looked a lot like geo textile and was highly fibrous in nature. When ripped, many more micro filaments could be observed leading the team to believe it would have a good surface area to volume ratio. Large sheets did not shred well and tended to remain large initially. Instead, the material "balled" and was incorporated as is.

- SAMPLE 8 products: these had been used for their intended function prior to delivery for trial use, as disposable food service/ consumption products. The SAMPLE 8 products already contained food waste and residues. The used products were strong and robust upon inspection; fibre-based plates and coffee cups, food trays with a thick woody leaf visual appearance and wooden knives and forks. When shredded, the products stayed in their original formats. This included where plates had been stacked on collection and in essence stuck together by food waste which remained after shredding. This reduced surface area to volume ratio in turn reducing composting speed.

- SAMPLE 9 Film used in sweet wrappers: this came in baled, compressed and was a large solid block of thin film, some of which was metallised (the metallised films are also certified compostable). The bales had to be broken and shredded twice to enable break up at which point there were still solid blocks within the greater mass. The small threads could be a windblown litter problem without the correct controls in place to minimise risk of material leaving site when processed outside. Envar already has these controls in place to ensure that this is not an issue.

N.B. all the above noted wastes were shredded using a Doppstadt 3060 biopower industrial shredder, which has a rough slow speed shred to a maximum of 400mm in any one plane. Although in reality, the shred is much smaller due to the grinding nature of its action as the material is pulled through the rakes, compacting and tearing against itself and the shredder body.

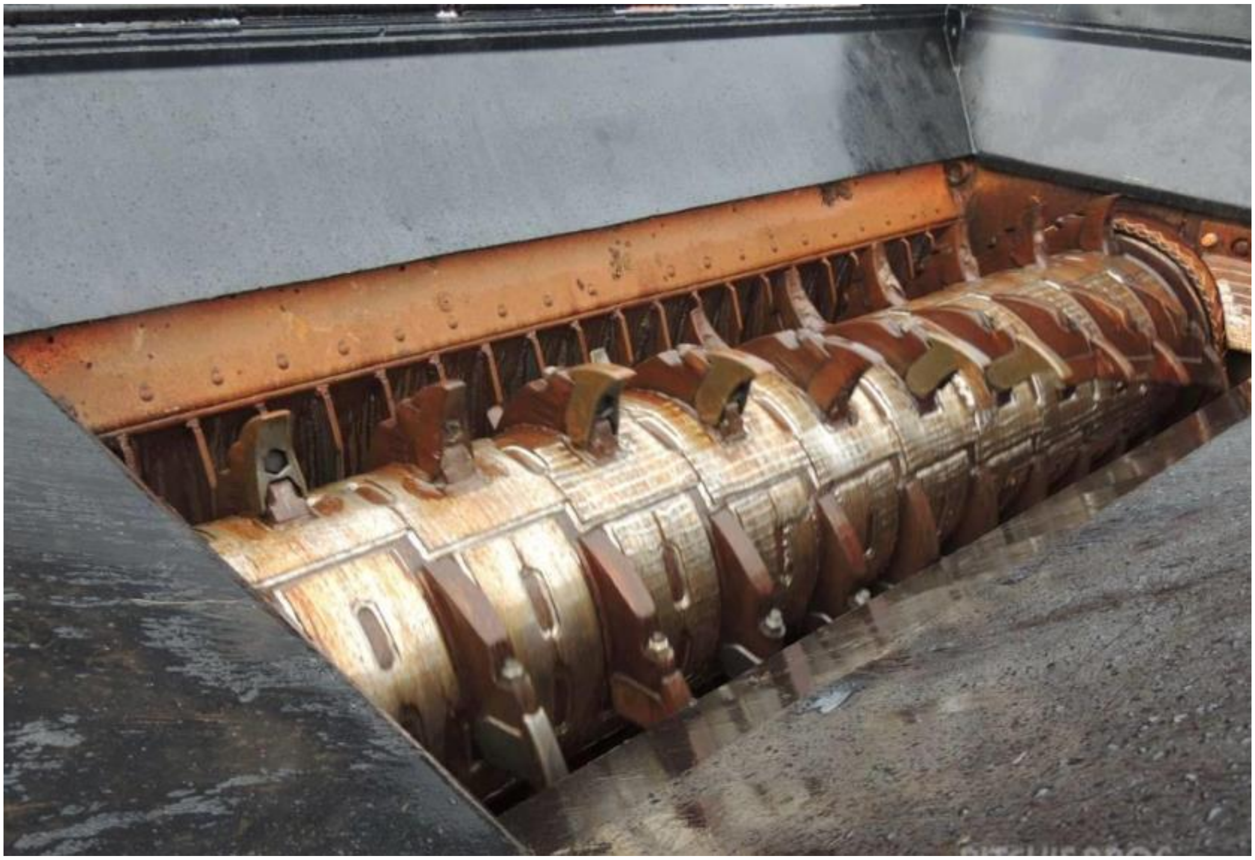

Figure 2- The shredding rotor on a Doppstadt 3060 Biopower - showing teeth and rake configuration. There is a further rake, which the teeth move through deeper into the machine.

Process Outputs

The process began in tunnel number G6 on the 21st of December 2022. The material was mixed, blended (see the material sheet for details on which materials were mixed with how much normal substrate) and processed in the same way Envar Composting Ltd feedstock would normally be managed, in line with the standard operating procedures and guidelines set by and managed within the company. The tunnel is loaded to the required capacity using large hydraulic wheeled loaders with high-capacity buckets. Once loaded the tunnel is sealed shut at both ends using the hydraulic sealed doors. The vessel used for this trial holds an average of two hundred tonnes of feedstock material. The material structure is improved via the addition of "oversize," woody sticks and branches – screened out from a composting batch that has previously reached the compost screening stage. This provides air gaps and air tunnels within the composting batch. Resulting in allowing airflow to support the facultatively aerobic bacteria which drive the process producing heat and enzymatic breakdown.

We chose a 5% load rate based on volume not weight ratio. The UK produces 9.5 million tons of food waste. 5% of that would mean ~500K ton of compostable plastic which represents ~ more than 20% of plastic replaced in the UK with compostables [1]. Thus a 5% load-rate represents a much higher % of compostables than what is considered feasible within the near future and therefore stress tests the whole process as being able to cope with the intended normal percentage easily.

Figure 3 - Material in the composting tunnel being processed between Christmas and New Year 2022. 50% through its allotted time in the IVC tunnel.

Liquid is added to the process periodically to enable this continued break down through microbial and hence thermal and chemical breakdown. After a high enough temperature to meet the animal by-products regulations has been achieved for a long enough period, the dampers on the tunnels are opened and fresh air from the reception hall is drawn into the tunnel with the top part of the tunnel exhaust vented to odour abatement systems and finally to atmosphere. The first or "warm up" stage takes an average of 24-48 hours depending on the material and the required speed of the process.

To explain further, material, which is lower in energy, often received during the winter period, takes longer to sufficiently self-heat as there is less readily available food in the material for microorganisms. In the summer when there is plenty of green, high moisture plant material being delivered, the increased bioavailability of these macronutrients speeds the process.

1 https://wrap.org.uk/taking-action/collections-recycling/markets-materials/organics-collection-sorting-reprocessing

The input tonnages to the site are lower in the winter months due to lower plant growth at that time of year and relatively little gardening activities by householders and 'green grounds' maintenance at premises compared with other seasons. These relatively low input tonnages allow the site to slow the throughput cycle of new material to maximise space and recovery for the following season. Therefore, the material remains in the enclosed tunnel for longer than it usually would compare to a summertime processing batch. No specific time is referred to for how much longer the material is left in the tunnel compared to the summertime processing, as this can vary dependant on the batch requirements at the time. Therefore, inferences can be made from the degradation profiles which have been prepared. Non-composted materials (such as part degraded bio packaging) are returned to the start of the process for re-composting. This is of particular importance when we consider the degradation profiles further in the following sections of this paper.

Non-composted material is returned to the start of the process and is used to reconfigure the C:N ratio of incoming food and green waste. There is some sortation which removes some traditional contaminant. However, a portion remains which is incorporated. The UK PAS system comments that all materials being reintroduced should be virtually free of contamination. However, in this context because the materials are biodegradable, they are not classed as contamination and therefore undergo processing once more. This means that a material that breaks down only 50% first pass will be resubjected to treatment and will be 75% degraded by second pass. When we look at surface area to volume ratio, we can consider the material likely to be fully degraded by third pass although further research would support this claim.

On 12th January 2023, 3 weeks after the trialled started (noting the trial commenced on the 21st of December 2022) the composting batch was removed from the G6 tunnel to the composting pad that hosts open windrows. This batch was kept separate, formed into a short, full scale cross section windrow. A short, vertical cross-section gap kept the windrow separate from other composting materials derived from the remaining onsite tunnels utilising the rest of the available length/ space of the outdoor composting pad and windrows. For ease of recording the segregated windrow was allocated the same batch number as the composting materials that were utilising the remainder of the pad length for that specific windrow (#1041). The batch record included 'along the length 'sections for recording windrow temperature and moisture assessments, dates, and number of times the windrow was turned, etc. The short windrow containing the trial materials was managed as per the normal process.

Figure 4 - Material from the batch being unloaded from the tunnel. The Actinomyces can be seen on the material as white strands. The heat can be visualised from the emission of steam.

Often in commercial composting, batches of material from multiple composting vessels or "tunnels" are combined into a larger windrow when they are removed. This is for space and turning efficiency using the compost turner. Because the windrows are up to 250m long and they maintain the same trapezoid profile across the entire 250m cross section the efficiency of air flow through the material remains constant and the microbial action continues efficiently through the entire mass.

Figure 5 -The segregated windrow, containing the compostable test materials/ packaging was placed at the end of "Row 1, Old Pad". This row has just been mechanically turned. The profile is a roughly rounded trapezoid.

The compost parameters are monitored consistently throughout the entirety of the composting process in the tunnel and recorded on the computer SCADA system for later review. The time temperature graph is shown below, please see *Figure* 6.

Each line on the graph represents a temperature probe that is inserted and remains within the composting mass during the entire in-tunnel phase. These temperature probes are handled from the roof of the concrete compositing IVC tunnel and are pushed into the material to about 0.5 to 1m in depth. *Figure 3* shows the probes inserted ready for the tunnel to be sealed and the process to commence.

Internal temperatures, gas flows and detailed technical data can be found on the "List of Marks" which is appended to this document. Please see Appendix I.

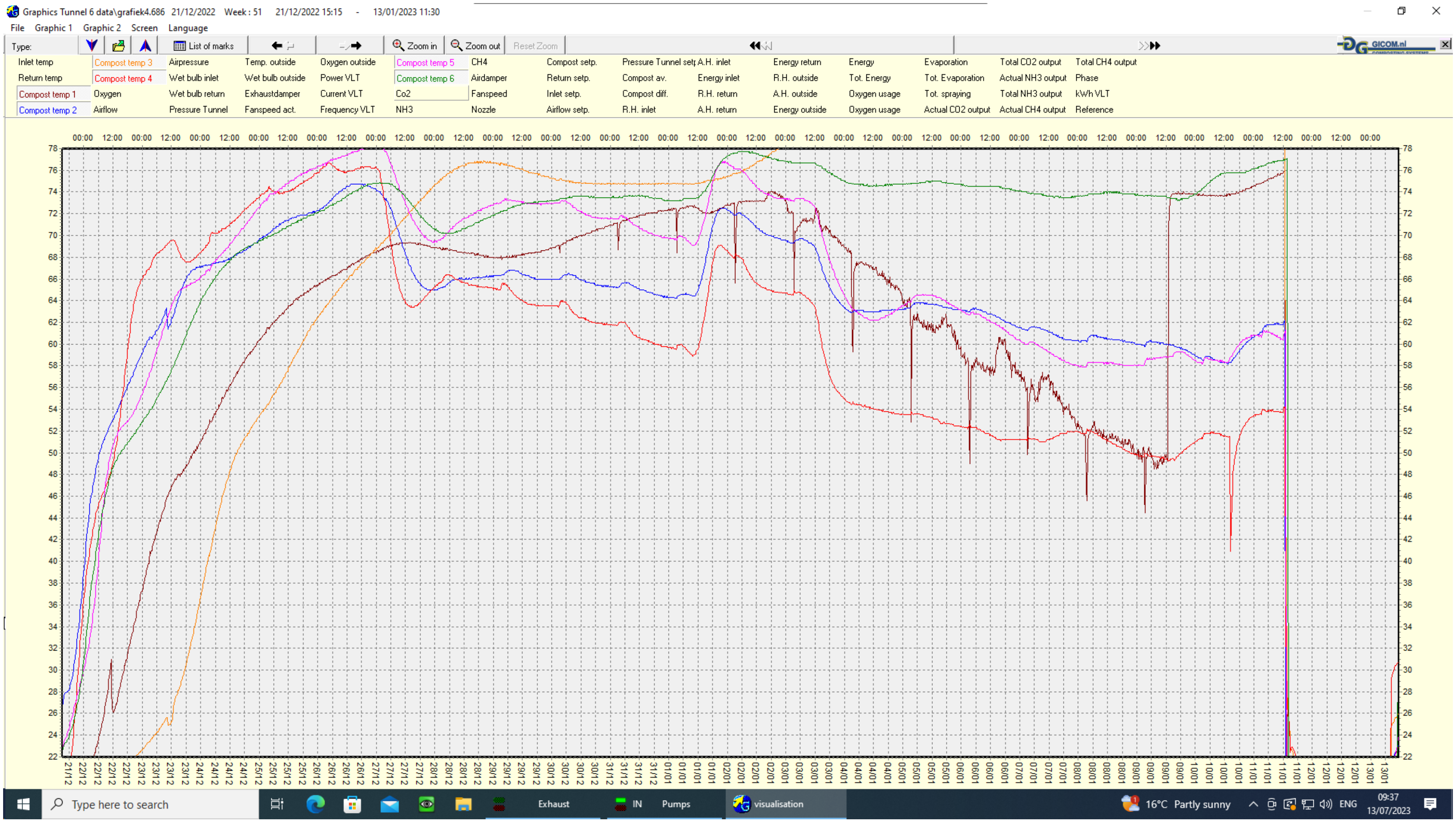

Figure 6 – Time temperature data from the computer. The controlled SCADA systems use process feedback to adjust the composting parameters, ensuring optimum composting conditions are maintained.

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Turning the material ensures the external material is moved to the centre of the composting mass, to ensure that over the period of the composting process it may be exposed to the same conditions conducive to break down as the rest of the mass is subject to for at least 50% of the composting time. The turning of the compost also provides for mechanical breakdown of the composting material through the teeth of the turner impacting larger particles and tearing fibrous or film like material such as compostable packaging. See *Figure 7*.

Figure 7 - Video still of blades of the compost turning machine, turning, and breaking material in the windrow containing the compostable test materials/ packaging.

Prior to turning the windrow, the compostable material/packaging samples in mesh bags, which were placed into the composting materials that formed tunnel batch G6, were located and removed. Post turning, the bags containing sample were put back into the segregated windrow and secured with markers (see *Figure 8*) to ensure the samples could be easily retrieved for analysis. These were periodically removed and taken to Envar's on-site lab for analysis as per the testing methodology and addendum.

Figure 8 - Composting windrow with markers showing the location of the sample mesh bags required for analysis during composting process.

The samples were buried into the composting batch (during in-vessel and windrow treatment phases) deep enough (see *Figure* 9), as per the methodology, to ensure the time, temperature and moisture parameters the rest of the mass received were the same as was experienced by the samples. The samples were then removed for analysis as per the methodology. The results were recorded in the onsite laboratory at the point of retrieval.

Figure 9 - Sample being buried in the material using a forklift truck to easily make a hole in the pile showing the bag being set at an estimated 1m deep.

Post completion of the composting stage, ensuring the duration of this phase was over a long enough time frame to enable Envar to produce sufficient data for degradation curves, the material was moved to the screening area for separation into compost product and oversize for reprocessing into compost once more (the material which is added to the front, reception end of the process). See *Figure 10*.

Figure 10* - Doppstadt SM-720-SA *screening of the compost.

The screening process was conducted using a Doppstadt SM-720-SA screening machine. These screeners work like a large rotating sieve, it's 10mm holes allow i the smaller particles to drop through and be conveyed to a separate pile for out loading. The "oversize" material which is too large for the 10mm holes is ejected from the rear of the screening drum. This oversize is stockpiled for reincorporation at the reception stage of material processing or separated into aggregate, wood and plastics for further recovery or recycling as biomass/ secondary aggregate.

When oversize is re-composted, it returns to the front, reception end of the process. A pre-condition of oversize re-composting is that it meets Envar's quality control criteria for inputs to the composting process , either 'as is' after screening or after action to sufficiently reduce the concentration of physical contaminants and the treated portion of oversize passing the further quality control check (as is allowed by REAL's Compost Certification Scheme Position on Technical Requirements provides their interpretation of parts of PAS 100 and/or the Compost Quality Protocol). Visible remnants of compostable items in portions of oversize for re-composting are not counted as physical contaminants because they are allowed input types, although care needs to be taken with how quality control checks differentiate compostable item remnants from non-compostable ones. Most composters will recirculate oversize with or without cleaning of plastics. Compostables would therefore be re-exposed to the composting cycle. Removal of plastics from oversize does mean some compostables (partially degraded) would be recovered for disposal or recovery. However, considering the degradation prior to this the percentage would be low.

The brushes that can be seen on the screening machine are used to clean or "pop" the 10mm drum holes as the barrel of the drum rotates to ensure the sieving is as efficient as it can be. Otherwise, the material forms a plug over the hole and the hole does not function to let material pass, eventually eliminating screening efficacy all together.

Batch data is collected via a mobile probe called a compost manager probe. When inserted the composting mass, the compost manager probe monitors various conditions within it. This is supplemented by a handheld temperature probe operators use to collect information on the processing material on a weekly basis.

Results

Results were obtained though several different methods as have been described within the methodologies of the process. These are available as part of the wider pack of the trial Documentation. The four methodologies were employed to gain the most reliable data which was possible given the many variables and constraints which would be experienced in an industrial setting. The experiment was purposefully conducted during the winter period when the material is at its lowest input energy state where material has less nitrogen and more carbon content in general as there are fewer green materials and the external temperature is coldest.

The recorded data was analysed internally by Envar Composting Ltd.

Samples in Mesh Bags – Method 1

A specific compostable material/ packaging sample was placed in a mesh bag without addition of any other waste or material. The same was done for each of the compostable material/packaging sample types. Whole tea bags and coffee pods were placed into their respective mesh bags, while the other sample types were ripped or cut by hand; this approach simulated what was likely to have happened if the samples had been prior fed into Envar's shredder. Each filled mesh bag was then placed into the in-vessel (tunnel) composting batch. The mesh bags' hole sizes were 3 mm by 3 mm.

20 pieces of each sample were put into each bag and weighed. This means 20 bags, sheets, pods, matts, or items.

Figure 11 shows that the sample types differed in their rates of decomposition over a 77-day (11 week) composting period, as measured by retrieving and weighing (on a fresh mass basis) samples from their mesh bags. Samples were returned to their mesh bags after weighing, except after last weighing on 8th March. All materials degraded within the period. Tests including the weighing of individual items ceased after the first few weeks. This was due to practicality, as it did not allow for the materials to be readily dried and weighed. It was considered these results from this test methodology would be unreliable as the materials degraded and broke up, meaning there would be no true/ definitive guarantee the sample was the same in volume as when it started. For this to work, a completely closed system would be required. Overall, the mini composter provides the required closed system and therefore the results produced from the mini composter should be considered as a replacement for this test methodology. Instead, all results in the main composting/ degradation trial through the IVC are based upon the weighing of the whole sample in mesh bags periodically removed and replaced throughout the process.

Figure 11 – Mass change over time of samples inside mesh bags (on a fresh mass basis), treated as per the in-vessel then outdoor windrow composting test methodology.

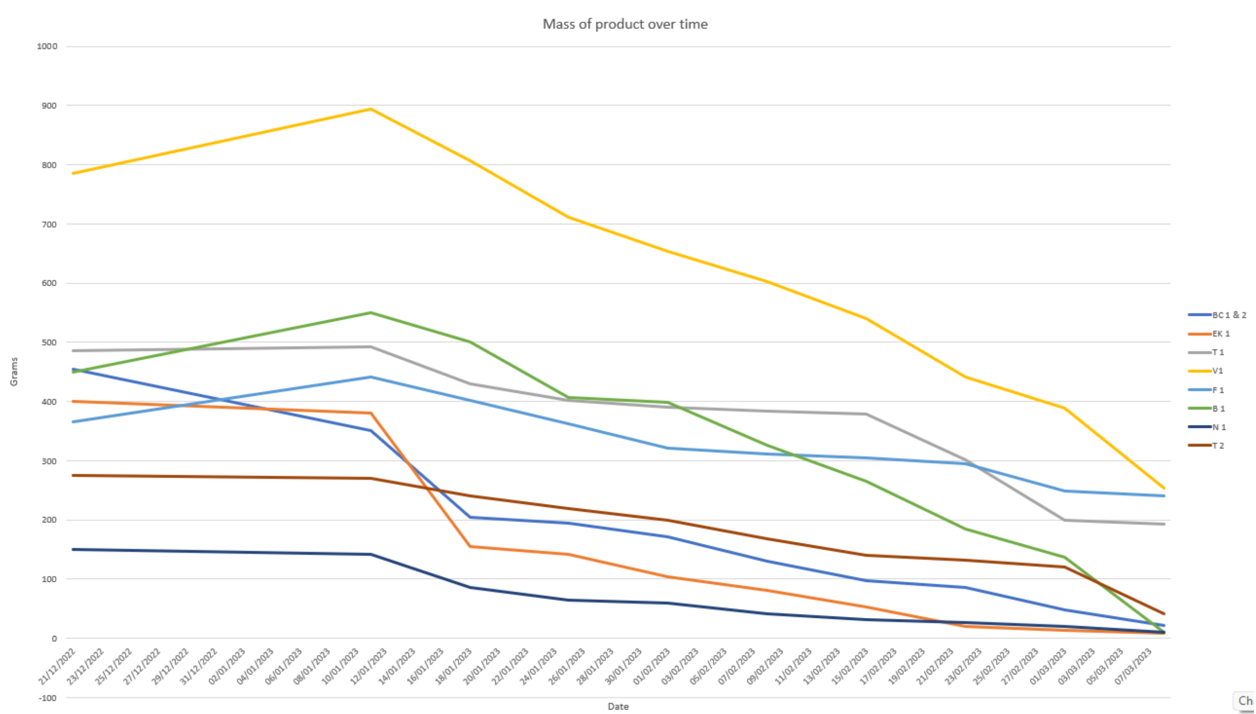


Figure 11 shows some materials gained mass throughout the initial 3 weeks of the trial. This is due to the absorption of water/ moisture from the surrounding composting mass into the sample as it begins breaking down through the cleaving of bonds and splitting of fibres. This was more evident in materials which are naturally based such as cardboard, paper and food use residuals such as 'spent' coffee grounds and tea leaves/ ground tea leaves; these maintain a large mass for an initial period after which their mass drops rapidly.

Rates of degradation are affected significantly by the format of the material, this has been extensively explained in the final part of this report. Baled, compressed, loose or shredded to a finer structure, will change the outcome significantly. The different formats of material that can be delivered for processing, and the issues that can arise from the differing ways of presentation, can, and have been, overcome by using the correct plant machinery that is readily available. This report should be read with this context in mind.

Table 2 - Percentage each material degraded over the in-vessel then windrow composting batch trial period.

Material	**Format material arrived in**	**End Degradation** (percentage loss of mass, on a fresh mass basis)
SAMPLE 7	Compound, Loose	97.78%m/m
SAMPLE 4	Tea bags, loose	97.75%m/m
SAMPLE 5	Unused Coffee pods, Loose	95.16%m/m
SAMPLE 6	Used Coffee pods, Loose	95.16%m/m
SAMPLE 3	Bags, Loose (14 mic. and 19 mic.)	93.33%m/m
SAMPLE 2	Bags, Loose (40 mic.)	84.73%m/m
SAMPLE 1	Bags, Loose (80 mic.)	67.64%m/m
SAMPLE 8	Tableware (Fiber and/or compostable polymer based) Semi compressed	60.41%m/m
SAMPLE 9	Film used in sweet wrappers, Baled and compressed	33.97%m/m
All		**78.85%m/m**

Table 2 shows the final, measured degradation percentages of each compostable material/ packaging sample type still found inside its mesh bags, its final mass as a percentage of its

mass at the start (mass changes, on a fresh mass basis, over 11 weeks from 21 December 2022 to 8th March 2023). Thicker materials, or those which were clumped together with less total surface area readily available for microbial colonisation, have less direct exposure to the composting conditions. Consequently, they tended to break down less efficiently. This is discussed in the anecdotal evidence section. Four of the compostable material/packaging samples lost 93 % of the mass they had at the start while the other sample types lost less. The average degradation of the entire range of sample compostable materials/packaging by the 11 weeks of composting stage was 78.8%m/m on a fresh mass basis (see Figure 12).

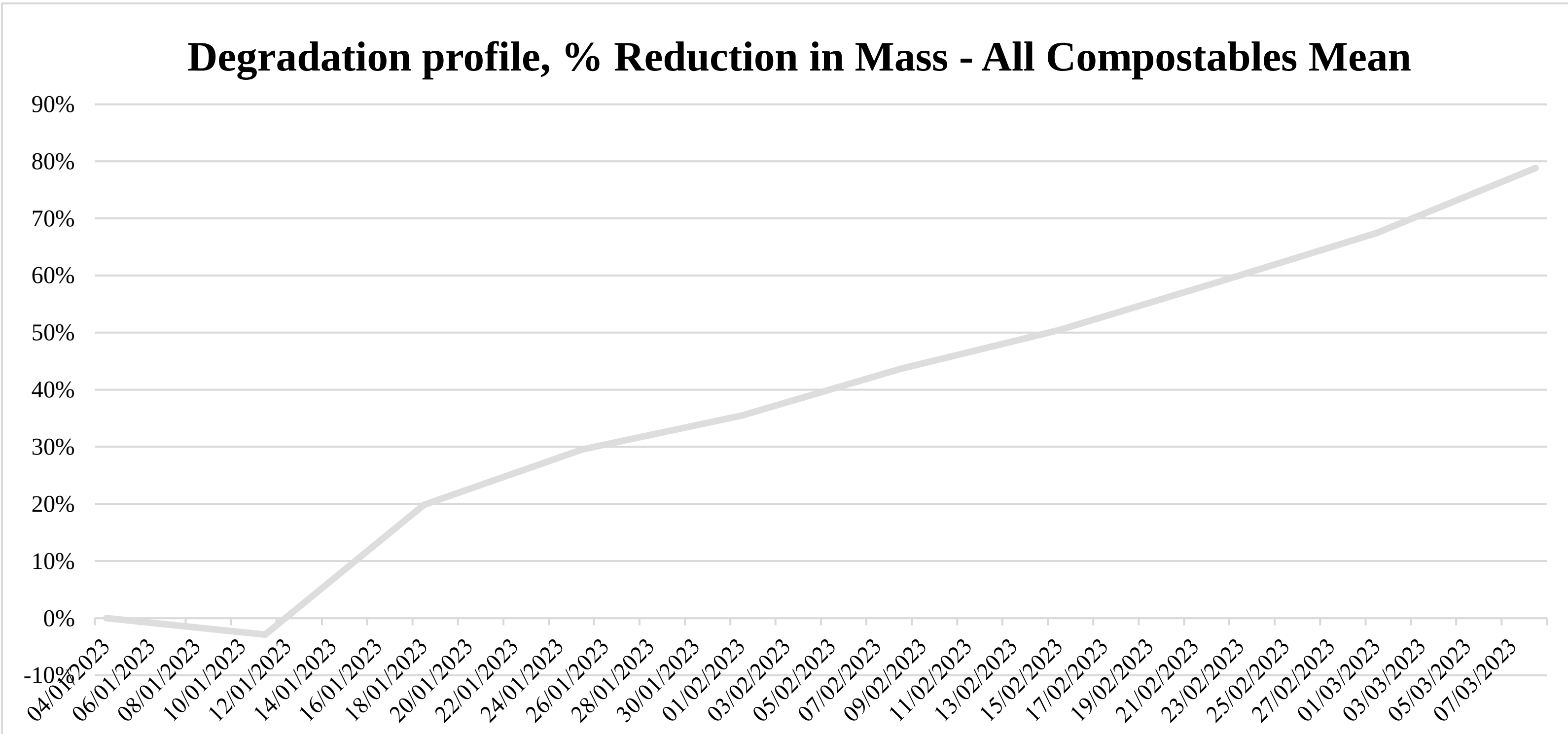
Samples in Mesh Bags – Method 2

A further methodology tried out was at intervals, retrieving, drying, and weighing the two largest pieces of compostable material/packaging from each mesh bag, returning them to their respective mesh bags and placing these back inside the composting batch (as it progressed through its in-vessel then outdoor windrow treatment). However, this methodology was stopped after a few weeks because practicality did not allow for the targeted materials to be readily separated from the other pieces without breaking when being dried and weighed. It was considered these results from this test methodology would be unreliable as some of the '2 largest piece' materials broke upon handling meaning that there would be no guarantee each sample piece was the same in volume as when it started.

Samples in Mesh Bags – Method 3

To quantify the loss of mass for each compostable sample over time when in contact with other composting wastes/materials (shredded biowastes the same as or like those put in the in-vessel trial batch) and under composting conditions, an enclosed system was required. Envar's mini composter provides such a system. Therefore, these results should be considered as an alternative method for quantifying compostable material/packaging mass loss as composting timescale progresses. This method is not subject to as much sample migration outside of mesh bags as is likely to have occurred in Method 1. Method 1 reflects what happens in commercial scale composting batches that are regularly turned as part of the process. Instead, all results are based upon the weighing of the whole sample in mesh bags that were periodically removed and then replaced at intervals during the mini-composter process. Those results are not included in this report as the mini-composter trial is on-going.

Figure 12 - Overall degradation profile, sum percentage mass loss of all sample compostable materials over 63 days (9 weeks) in a sequence of in-vessel then open-air turned windrow composting.



Degradation Trial – Samples Placed Directly in Main Composting Mass – Method 4

A further method used for researching the degradation of sample compostable materials was conducted by placing them directly into an in-vessel sized composting batch, i.e. not having first put each sample type into a mesh bag. Samples were taken from the composting batch as it progressed through the in-vessel then outdoor windrow composting process. These samples were then lab analysed and reported upon.

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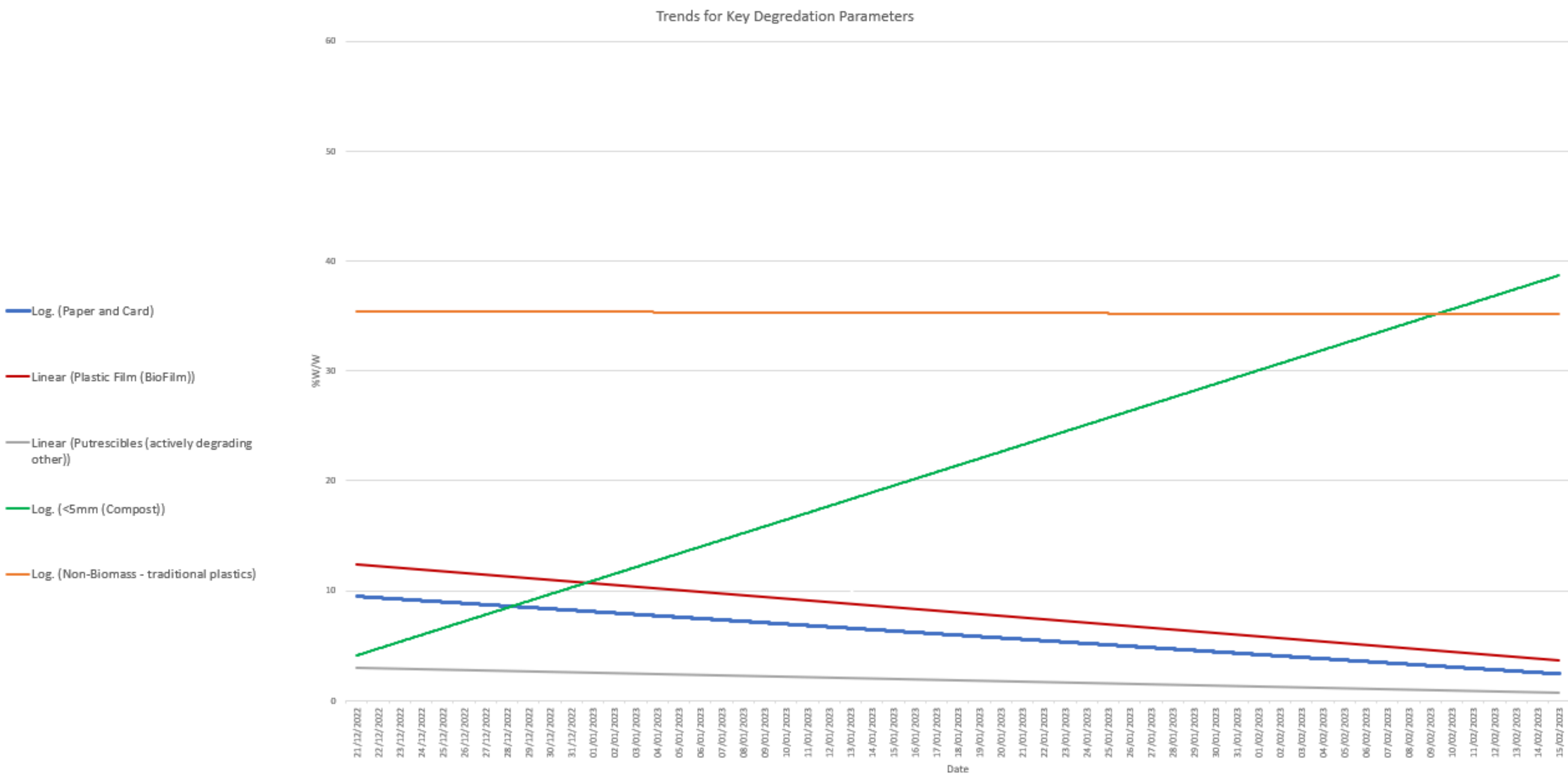
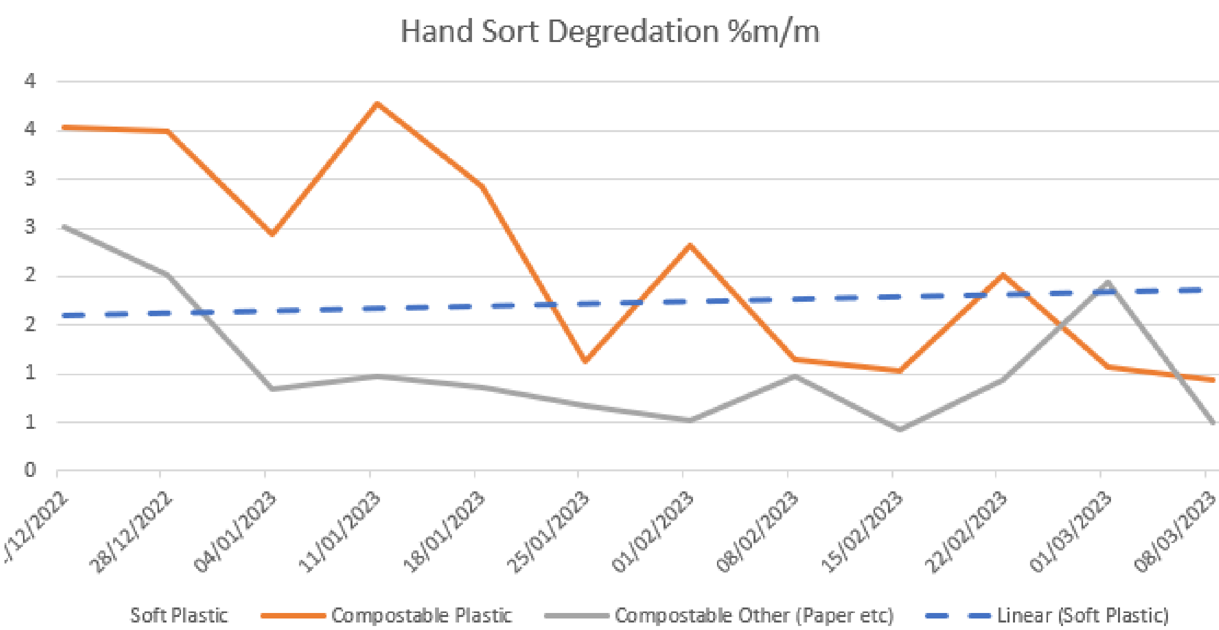
Figure 13 - Trendlines for degradation of key materials during 56 days (8 weeks) of in-vessel then windrow composting.



The less than 5mm small particle material, increased rapidly over the composting process as is shown in figure 13. At the 56-day (8 week) stage of composting measured in this part of the trial, most of the less than 5 mm particles visually appeared brown and typical of compost. These less than 5 mm particles represented over 40% of the total mass of the composting batch at this 56-day stage. This is expected in normal composting processes for most on-site batches.

All other materials showed an expected negative fall during the same period except – traditional plastics. The percentage represented by compostable plastic films fell steadily. Over the same period, the percentage of total batch mass represented by traditional plastics stayed almost level. This data shows a reduction in the collective total mass of compostable plastic films as a percentage of total composting batch mass.

Figure 14 - Hand sort degradation profile per material for 56 days (8 weeks) of in-vessel then windrow composting.



The composting batch was also sampled at intervals (see Figure 14) and hand sorting of those samples was conducted internally by Envar in their in-house lab. Materials were hand separated and visually assessed for ascertaining which material was which.

The materials were hand sorted into visual categories with the main ones being reported as per the above figure 14. No specific weight or volume was taken from the material as this was not deemed to influence the outcome so long as a minimum was sampled. Therefore, the team sorted one large wheelbarrow of material per sort which equated to roughly 20kg samples as per the standard sampling procedure of taking 12 sub samples and mixing. Spilling into quartiles and taking two of those quartiles to fill the barrow.

The hand sort showed materials (combined compostables supplied for the trial) reduced from starting percentages of between 3% m/m and 4% m/m in the sample's representative of the whole composting batch to near 1% m/m by the end of the 56-day (8 week) period. In contrast, the percentage by mass of traditional plastics in those samples stayed between 2.1 and 2.9 % m/m with a weak trend of increase as a percentage of total sample mass over the same period. stable apart from expected sampling variation.

Anecdotal Evidence

Pictures taken during the composting process show key moments in the breakdown of the samples of compostable materials supplied. Examples include the clumping of certain plastics, the stacking of some compostable materials preventing their rapid breakdown and other compostable materials rapidly breaking down due to loss of their degradable innards, such as tea bags and coffee grounds.

Figure 15 shows post tunnel paper plates. The paper plates in the foreground of the picture had been stacked as they were disposed of. This was due to having stuck together with a type of residue. This residue was still present to an extent during the analysis, which was after tunnel composting (3 weeks after the composting batch began its tunnel phase). The plate

Figure 15 – SAMPLE 8 after tunnel phase of composting, found to be stacked together which clearly reduced break down rate.

in the background is a single item which has been “balled up” by the shredder (where the material rolls and tears into a round shape). When handled, the intact, stacked plates were still strong and resisted tension (see figure 15, foreground). The plate in the background of figure 15 tore easily and was more of a sludge consistency, more crumbled upon handling. After six weeks of composting some of the compostable plastic bags had almost disappeared. The thicker consistency bags were starting to become brittle and turn into shards of material, which turned to dust when handled roughly. The shards were brittle to the touch. Where the material was bunched together it was stronger and less broken down.

Figure 16 – SAMPLE 1 & SAMPLE 2 Bags after 4 weeks.

Figure 17- Fibrous material- (SAMPLE 7)

The fibrous compound (SAMPLE 7) geotextile style material had broken down into balls of wet and malleable particles, which was easily crumbled into smaller particles when pressed between fingers.

Figure 17 – SAMPLE 5/ SAMPLE 6 Coffee pods and SAMPLE 4 tea bags at 4 weeks of composting stage. The materials essential had already fallen apart of did on gentle handling.

Figure 18 – Sample 9 film used for sweet wrappers at 3 weeks of composting stage.

PAS100 Tests – Compost Quality

The trial-relevant composting windrow was screened between 24th February and 1st March to produce a 'compost grade' with particles largely within a 0 - 10 mm size range (the same size range for which Envar has a certificate of compliance with PAS 100, the Compost Quality Protocol and REAL's Compost Certification Rules. The trial-relevant screened compost then underwent a period of aerobic maturation, as is allowed within Envar's PAS 100-related standard operating procedures. The screening step also removes, as best as practicable, physical contaminants larger than approx. 10 mm in any dimension that had entered the composting process.

PAS100 and the Compost Quality Protocol allows compostable packaging and non-packaging /plastic product to be fed into a composting process on condition they are independently certified compliant with at least one of the British and European standards BS EN 13432 or BS EN 14995 or the North American standard ASTM D6400.

As part of checks that compost is at least the minimum quality specified in PAS 100 - which includes limitation of compost use-related risks to humans, animals, and the environment - and meets any further quality requirements in the producer's Quality Policy (Envar's in this case), a representative sample was taken from the screened compost. It was sampled and delivered on 17th April (117 days or 16.7 weeks after composting batch formation) to an independent laboratory for analysis, as per the suite of tests specified in PAS 100.

The compost sample results passed every test with the exception of contamination by glass (retained on the sieve with 4mm holes). This contamination was almost certainly due to contamination from another source (food, garden, or combined waste) outside of the compostable packaging supplied for the trial, and with which the compostable packaging was combined before being loaded into the composting tunnel. Most of the trial packaging was delivered on its own and the remainder of the trial packaging was collected and delivered with food waste passed Envar's visual quality check criteria on waste load acceptance for composting.

After Envar reviewed the lab test results a further sample was taken from the same screened compost and sent to the independent lab for physical contaminants testing. This sample passed its physical contamination tests.

Electrical conductivity of 1595µS/cm@ 25°C is standard for green- and food-waste derived compost and low enough that the compost, in terms of this characteristic, was suitable for blending with other media to make a quality growing medium or to be spread as a soil improver in agriculture, soft landscaping and other market sectors in which the Compost Quality Protocol allows certified composts to be used.

Plant growth tests comprise tomato seed germination and growth over 28 days, comparing plants that germinate and grow in the sample compost-plus-peat based 'test' mixture with those that germinate and grow in a peat-based control. Plant germination in the test mixture was 100% when compared with the control and there were no weeds germinating in the material. Average top growth per plant grown in the test mixture was 91.86% when compared with the control which is positive (a pass result) and is as expected.

PLANT RESPONSE ~ PART 2 ~ GROWTH OF GERMINATED OF TOMATO PLANTS

REAL MT PRT v1: Method for testing plant response to composted material and contamination by weed seeds and propagules.

Tomato plant top growth 28 days after sowing	**Peat Control**			**Peat + compost test**			**Overall**	**Unit**
	Tray 1	Tray 2	Tray 3	Tray 1	Tray 2	Tray 3		
Total number of true leaves per tray	N/D	N/D	N/D	N/D	N/D	N/D		number of tomato plants
Mean number of true leaves per plant in tray	N/D	N/D	N/D	N/D	N/D	N/D		
Total plant mass [1] per tray	63.27	64.53	43.80	64.32	55.86	38.30		g top growth fresh mass
Mean mass per plant [1] in tray	6.3	6.5	4.4	6.4	5.6	3.8		
Mean mass per plant [1] for all test trays as % of mean mass per plant [1] for all control trays, by 28 days after sowing							**91.86**	tests as % of controls
PAS 100 minimum performance required							80	
Pass or Fail							**Pass**	g top growth fresh mass
Mean mass per plant[1] grown in all 3 control trays							5.720	
Assessment of test validity	Valid if ≥ 2.00 g per plant [1] in control trays						**Valid**	

[1] Tomato plant top growth N/D = Not Determined

Figure 19 - Plant Response Tests

The compost sample's stability of 4.3mg CO_2 / g organic matter / day showed it was much more stable than the minimum stability required - 16mg CO_2 / g organic matter / day for normal PAS standard composts. Stability is a measure of the compost's breakdown rate, i.e., the rate per day at which carbon dioxide is released per gramme of organic matter in the compost.

Discussion

Degradability in Envar's industrial composting systems

Each compostable material/packaging item type in its mesh bag degraded at a different rate and to a different level of completeness by the end of 11 weeks of in-vessel then windrow composting period. Materials which clumped together and had a lower surface area to volume ratio did not fare as well as those which were more porous in nature, thinner or more easily broken up.

The data from the hand-sort and the bag samples shows us clearly that some compostable materials/packaging types degrade faster than others. This is as expected, as the products are designed to have structural reinforcement or designed disabilities. From the evidence we can discuss the following features of compostable packaging:

- Evidence shows mass loss and reduction in % m/m that compostables represented within their in-vessel then windrow composting batch. Some materials lost mass and reduced as a % of the composting batch more than others, and timescales of different assessment methods were different. Materials have a different rate of breakdown dependant on the material they are made from.
- Materials break down differently depending on surface area to volume ratio.
- Physical presentation of the material affects its ability to process and break down effectively. This means easy-to-procure, available pre-treatment is a viable option for packaging materials, e.g. granulation machinery.
- Risk to the environment from final compost is low to negligible.

The materials that broke down at a more rapid/ increased rate were the SAMPLE 7 material (geotextile type configuration), coffee pods, tea bags and green compostable bags. These materials had a large surface area to volume ratio and were porous, being easily shred through a slow speed shredder. It is also worthwhile noting that the above-mentioned materials arrived at site in a loose format for processing.

Materials which broke down at a reduced rate in comparison to the materials noted above, were presented in bales. The bales failed to properly separate when processed through the slow speed shredder. It is perceived that a high-speed shredder which produces a finer grade material, would have been more effective in breaking the bales up. Thus, giving a better ability for this material to receive full exposure within the composting mass. However, clumps of material from the baled format remained using a slow speed shredder with the compost turner as an aid to break the material apart. The breakdown profile was not as expected at the end of full-scale composting degradation trials in comparison with the (currently ongoing) mini composter trial; the latter may show that there is a more efficient way of processing this material to ensure it is properly broken down in the process. This may involve smaller cutting or the non-baling of the material in the first instance. The reduced degradation was not due to the material itself but due to the format of delivery. This can be and has been overcome by addition/ further processing to enable a higher surface area for composting.

Semi compressed material which is by form stacked, such as a stack of cups or plates would also reduce the surface area to volume ratio and slow the degradation rate. There are solutions available such as fine-tooth shredders which can readily solve this issue should the market for compostables be sufficient to support this extra step. No technology advancement would be required for this.

A key point to take from this study, for all materials tested, is the more contact the material has with the composting mass, the more rapidly it breaks down. This key point allows for the further development of compostable packaging pretreatment methods, ensuring the reduction in particle size. It is important to note that the particle size must be smaller than that which food and green waste is currently processed to, to ensure maximum efficiency. This may provide for an even better breakdown profile than is currently experienced.

There is a residual amount of material after the composting process termed oversize, and it largely consists of very coarse woody particles retained by the screen when screening the compost. This may be viewed as being a wasteful part of the process if the oversize material is sent to an energy-from-waste combustion plant or sent to disposal, e.g., landfill. However, at Envar's facility, the oversize fraction tends to be managed in two different ways. Portions of oversize that pass input quality control criteria - either 'as is' or after action to sufficiently reduce physical contaminants and the portion passing its further quality control check - are reincorporated front-end, into incoming material to amend the mixture's carbon to nitrogen ratio (C:N) and provide structure. Envar's facility often reincorporates portions of oversize that pass input quality control criteria. This reincorporation allows the partially broken-down compostable materials/packaging in the oversize to be exposed to the composting process for an even longer period at a reduced size state (with a larger surface area to volume ratio), which further increases their break down rate.

Some portions of oversize are instead processed to prepare it for off-site use as a solid-recovered fuel. This involves on-site removal of residual plastic (all-types) and other physical contaminant types from the wood fraction as best as practical, the latter resulting in a solid recovered fuel for combustion at energy-from-waste plants, either being used in the UK or baled and exported to European power stations. This would also be the fate of any traditional plastic often containing a greater level of harmful compounds than the compostable polymers, whose contents tend to be significantly plant-based, and paper/card materials, which are also plant based. The plant-derived carbon in compostable polymers and paper/card materials makes them carbon neutral rather than a hydrocarbon-based traditional plastic, which is carbon positive.

Viability

Considering that Envar's industrial composting process already accepts and handles certified compostable waste packaging and non-packaging waste item, successfully recycling them using its the industrial composting process; the clear results of this trial show that including compostable materials/packaging with food and garden wastes does in fact produce a quality compost, which is safe for use in agriculture and horticulture. It is considered viable that compostable packaging and non-packaging items should continue to be a part of the collection and treatment of food wastes and food plus garden wastes in the UK. This will help reduce 'carbon-dioxide-equivalents' emissions and the reliance on non-renewable plastic primary packaging for food products and other non-packaging, food-waste relevant plastic products. Non-renewable plastics also suffer in food packaging scenarios. Due to the food contamination element on the packaging, this then requires disposal in line with the ABP requirements resulting in reducing the disposal routes available, making it more difficult to mechanically/conventionally recycle the packaging with any sufficient value to make it worthwhile/feasible for the consumer or local authority biowaste supplier.

The other benefit of traditional plastic product displacement in targeted food-contact and food waste collection applications is the reduction of non-biodegradable contaminants in the final compost which, if present, could potentially be applied to land through error or design. For every piece of traditional plastic displaced and replaced by compostable plastic in a biowaste stream, the effect is twofold; a contaminant is removed and replaced with an item that contributes to renewable carbon and microbial content in the compost product, aiding soil health. The same is true where compostable versions of food-contact relevant products displace those made of glass, metal, or other non-compostable materials, in applications where the item is likely to be discarded food-contaminated.

Disposal is often the part of the waste-management chain which causes the contamination of food and garden waste by physical contaminants (e.g., glass, metal, and non-compostable plastics). For example, when a person is required to know (dependant on how their local authority dispose of each waste stream collected) when to put a food tray in either their food caddy or food and green waste bin. If this material were compostable, reliance on the choice of individuals would be reduced and the system is strengthened by the reduction of risk of mistake or ignorance when the public dispose of packaging and non-packaging wastes. This shall be studied in further detail in other trials conducted the UK Compostable Coalition.

Conclusion

The compostable packaging trial showed that materials break down effectively in the composting process and residues are either returned to the process or recovered in a safer, less carbon intensive way than traditional alternatives. The compost supported plant germination and growth when tested according to the PAS100-specified test, and the PAS-suite of tests and results showed that the compost met each of PAS100's minimum quality requirements.

The use of the compostable packaging and non-packaging in targeted, food-relevant product formats reduces the risk of biowaste contamination by non-compostable plastics. This protects the environment from potential harm by displacing traditional plastics which arrive at composting facilities and are difficult to entirely remove during waste pre-treatment and at other opportunities during the composting process. When present in an industrial composting context, the traditional plastics that are removed from the process are less likely to be sent for mechanical recycling as they do not have a large value and chemical recycling for traditional plastics is not yet well developed in the UK. By composting food-waste relevant compostable packaging and non-packaging products instead, the value is to the environment and to the end compost product producer.

Notes on Methods Used and Conclusion Clarity

1. The "in bag" experiment gives the composting outcome a worst-case scenario because the experiment does not allow the material to spread as it might do in the normal composting process.
2. Oversize items that do not break down to the required PAS100 specifications are likely to go round again – possibly more than once, so long as they are certified compostable materials.
3. The final product of compostable breakdown is stable organic molecules such as lignin and cellulose, and bacterial biomass, water, and CO_2.

Appendix I

List of Marks .TXT

grafiek4.686.txt

Instructions

- Save the file as a text file in an appropriate location.
- Open Microsoft Excel.
- Go to file -> open.
- Open the file.
- Select CSV delimited using commas.
- "Save as" Excel workbook.