‘ENVIRONMENTAL PACKAGING’

A thesis submitted for the degree of

Engineering Doctorate in “Environmental Technology”

by

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ABSTRACT

The food packaging industry is a £300bn global industry growing at a rate of 12% per year and increasingly favouring polymer or polymer-based materials. This generates 58m tonnes of "plastic" packaging waste annually in the EU and poses significant challenges for management given existing legislative constraints and increasing concerns surrounding the environmental impacts. The government, consumers, food retailers and pressure groups are all driving the demand for biodegradable packaging from renewable resources that can be disposed of with reduced impacts to the environment. Green Peace has devised a pyramid classification system of "Poisonous Plastics", which ranks plastics in terms of their harmfulness to the environment. They are campaigning against the use of oil-based materials and advocating the take up of biodegradable materials.

The market for biodegradable food packaging is expanding rapidly but is still in its early stages of development and has not reached a critical mass to achieve significant market penetration. This is predominantly due to a lack of suitable materials that meet all environmental, functional and economical requirements. Whilst the long-term solution requires continued efforts in materials research and development, in the shorter term, changing working practices can abate the environmental impact of the industry.

This research project tackled the challenge of environmental packaging from several directions:

A novel starch-based material was developed that would fill the current gap in the food packaging market and facilitate recovery of the used materials by home composting.

Using the sponsoring organisation as a case study, it was proved that by changing working practices by increasing rework and re-processing waste material for use in lower grade applications, both manufacturing costs and environmental impact can be reduced, thus benefiting both industry and the environment.

A Life Cycle Assessment of selected biopolymers and oil-based polymers confirmed Green Peace's damning view of PVC and highlighted the need to develop biopolymers further.

A domestic composting study of a range of commercially available "biodegradable" polymer materials revealed that a number of biodegradable packaging materials may typically biodegrade well in industrial high-temperature composting systems but fail to biodegrade under a low-temperature home composting environment and thus alerted the potential pitfall in waste management of some biodegradable polymers.

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LIST OF ABBREVIATIONS

APET	Amorphous Polyethylene Terrathalate
BA	Bio-additives
CEN	European Committee of Standardisation
CO	Carbon Monoxide
CO_2	Carbon dioxide
CPET	Crystalline Polyethylene Terrathalate
DEFRA	Department for Environmental Food and Rural Affairs
EI	Eco Indicators
EngD	Engineering Doctorate
EPS	Expanded Polystyrene
EPSRC	Engineering and Physical Science Research Council
EVOH	Ethylene-Vinyl Alcohol
GMO	Genetically Modified Organism
GPS	General Purpose Polystyrene
H_2	Hydrogen
HDPE	High Density Polyethylene
HIPS	High Impact Polystyrene
KPI	Key Performance Indicators
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LDPE	Low Density Polyethylene
NGO	Non-Governmental Organisations
PAS	Publicly Available Standard
PBSA	Polybutylene Succinate Adipate
PCL	Polycaprolactone
PET	Polyethylene Terrathalate
PHB	Polyhydroxybutyrate
PLA	Polylactic Acid
PP	Polypropylene
PPE	Pactiv Packaging Europe
PPP	Poisonous Plastics Pyramid

PS	Polystyrene
PVC	Polyvinyl Chloride
PVOH	Polyvinyl Alcohol
RE	Research Engineer
REPA	Resource and Environmental Profile Analysis
SETAC	Society of Environmental Toxicology
SWOT	Strengths, Weaknesses, Opportunities and Threats

CHAPTER 1 EXECUTIVE SUMMARY

1.0 Executive Summary

The following chapter is an executive summary of the Engineering Doctorate (EngD) research project 'Environmental Packaging.' This section gives a brief introduction to the EngD Programme in order to describe the overall framework of the research work included in this thesis. The following sections of the executive summary describe in more detail the research carried out:

- Section 1.2: A description of the research topic and research project objectives
- Section 1.3: A summary of the research methodologies applied
- Section 1.4: The main results generated from this work including highlights of the contribution to knowledge and papers submitted for publication in scientific peer-reviewed journals
- Section 1.5: The commercial application of this research in terms of the benefits to Pactiv Europe, the sponsoring organisation
- Section 1.6: Provides an overview of the structure of this thesis.

1.1 Background of the Engineering Doctorate (EngD) in Environmental Technology

This section gives a brief introduction to the EngD Programme and describes the overall framework of the research work included in this thesis.

The Engineering Doctorate Programme (EngD) is a four-year research degree awarded for industrially relevant research, based in industry and supported by a programme of professional development courses. The EngD Programme is sponsored by the Engineering and Physical Science Research Council (EPSRC) and was set up in response to industry demand for more industrially orientated research. The industrial perspective of the work included in this thesis was instigated by Pactiv Europe who also provided additional funding to the EPSRC sponsorship, as required by the EngD Programme.

The work included in this thesis was carried out within the EngD centre in Environmental Technology managed jointly by Brunel and Surrey Universities. All research projects undertaken at the Brunel/Surrey EngD centre follow the theme of "Environmental Technology" and aim to "provide graduates with the necessary skills to balance environmental risks with all of the traditional variables of cost, quality, shareholder value and legislative compliance." The Brunel/Surrey programme aims to balance a number of competing interests. The research engineer (RE) must meet both academic and industrial requirements of the research while taking into account the environmental issues of the project undertaken. The following diagram (Figure 1.1) sums up the three elements of an EngD research project.

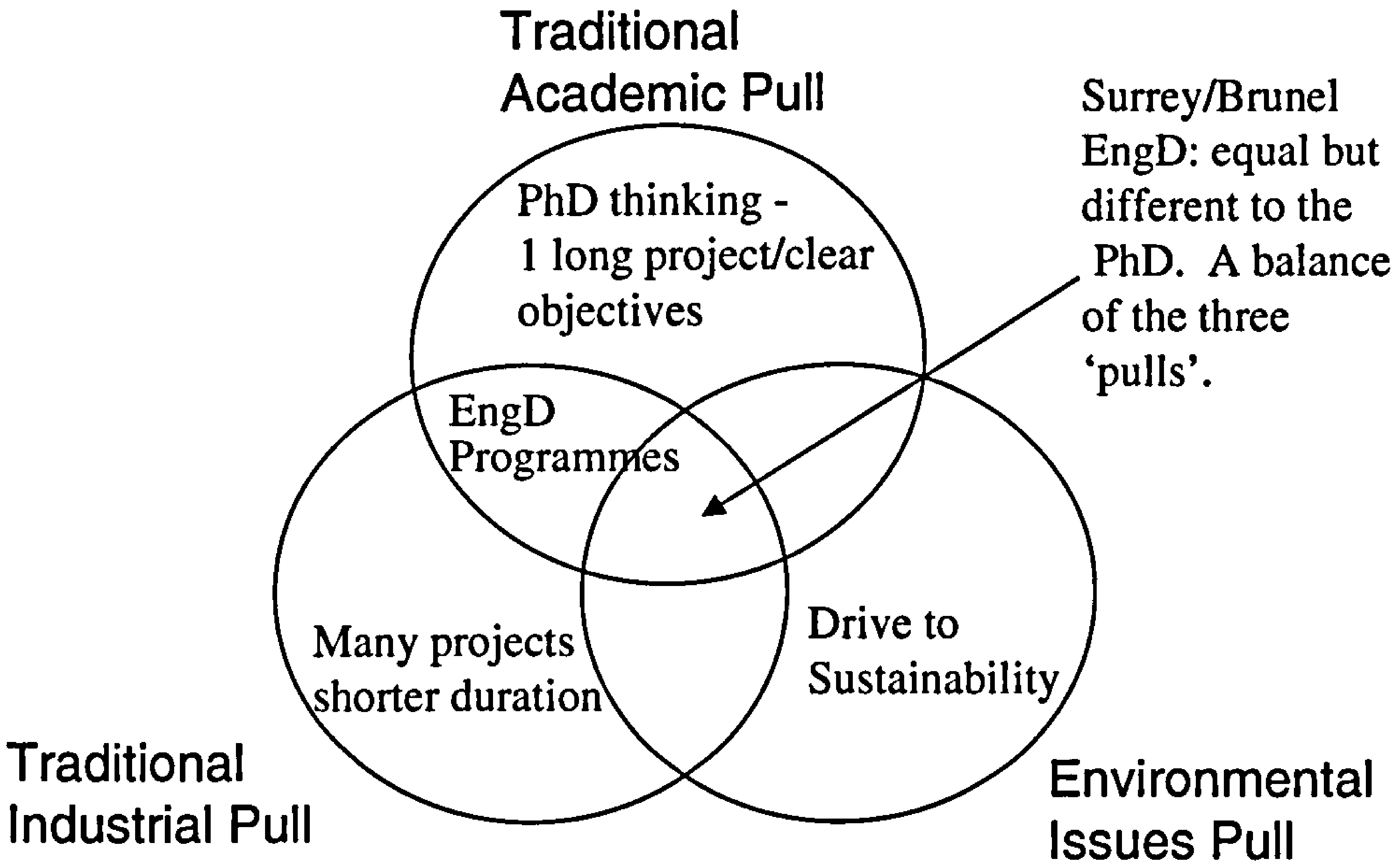

Figure 1.1: The three elements of an EngD research project

The EngD programme includes core and elective modules that aim to:

- Present a view of the relationship between Engineering and the Environment including sociological aspects, which can used in the research projects
- Provide professional development in key business skills and competencies
- Close any gaps in the knowledge required to undertake the research project

The modules taken and successfully completed during this research are as follows:

Year 1	Induction course: Communication & Leadership I
	Sustainable development
	Life Cycle approaches
	Research methodology
	Social Research for Environmental Strategy
	Environmental hands-on review and audit
	Risk Perception and communication
	Sustainable Development
	Getting started on your writing up
	Advanced Life Cycle Assessment
	Advanced leadership
Year 2	Environmental auditing and management systems
	Writing a scientific paper
	Decision making for environmental strategy
	Environmental Law
Year 3	Economic approaches
	Energy
	Materials
Year 4	Talking to the media
	Writing up your portfolio
	Financial Management

The EngD candidates also present their research at the annual EngD conferences, which are attended by all EngD candidates, supervisors and invited delegates. Presenting at the EngD conferences provides the opportunity to raise awareness and understanding of the research topic. From the research conducted in this thesis, the following paper and poster were written and published for the EngD conferences:

Davies G, Tonkin J and Song J (2003) *Environmental Packaging*, Engineering Doctorate in Environmental Technology Annual Conference 2003, Brunel University and the University of Surrey, 25-26 June 2003.

Davies G, Binney G, Song J and Murphy R (2005) *End of Life Management for Biopolymer Packaging*. Poster Engineering Doctorate in Environmental Technology Annual Conference 2005, Brunel University and the University of Surrey, 11-12 Jan 2005.

1.2 Introduction to the research topic and objectives

This section briefly summaries the Eng D research project and the objectives. A more detailed consideration of the research topic can be found in Chapter 2.

1.2.1 Research topic

The food packaging industry is a £300bn global industry growing at a rate of 12% per year and increasingly favouring polymer or polymer-based materials. This generates 58m tonnes of "plastic" packaging waste annually in the EU and poses significant challenges for waste management given the constraints of existing disposal facilities and the increasing concerns surrounding the environmental impacts. In the short term, the plastic food packaging industry must look for solutions to reduce environmental impact by waste reduction during processing and production of oil-based and non-oil-based packaging. This involves changing working practices to promote segregation of waste materials for optimum waste management of both oil-based and biopolymer materials. Meanwhile, the government, consumers, food retailers and pressure groups are all driving the demand for biodegradable packaging from renewable resources that can be disposed of with minimal damage to the environment. This provides the industry with an opportunity and a challenge to find long-term solutions using more sustainable renewable alternatives, which can be recovered by composting to reduce landfill and minimise the damage to the environment.

This EngD project aims to tackle the problems associated with implanting the two potential solutions in the context of plastic food packaging industry.

The application of biodegradable polymers in packaging there are a number of issues to be addressed:

- Although there are several "biodegradable polymers" on the market, the industry is still in its infancy. The market has yet to come up with a commercially and environmentally viable solution that meets food-packaging requirements and hence more research and development
- At present, there are numerous types of biodegradable polymer packaging materials with varying uses, properties and hence waste treatment

requirements; for example, PVC is best suited to disposal via the current municipal waste stream whereas PLA is best suited for industrial composting. This confusing landscape results in an insufficient understanding of optimum disposal methods for the various materials. Most existing biodegradable materials are only biodegradable under industrial conditions. Consumer awareness of this fact is low and there is no explanation on items of food packaging. In order to meet environmental requirements as well as sustainability, post-consumer materials designed for both domestic and industrial composting environments should be considered. All materials should at least be clearly labelled with the most suitable end-of life route.

- Although one may feel intuitively that biodegradable polymers are more environmentally friendly than oil-based polymers, critical cradle-to-grave assessments must be carried out to identify the pros and cons in comparison with oil-based plastics to fully understand the potential benefits and pitfalls of biodegradable polymer alternatives. Life cycle assessment is a useful tool for understanding the true environmental impacts.

1.2.2 Research objectives

There were five principal aims of the research carried out during the EngD:

1. To reduce waste by improving material utilisation within current processes and working practices using existing technology and oil-based materials.

2. To assess the suitability and economic viability of new-generation "biodegradable"/"sustainable" materials in the market for food packaging applications.

3. To develop an alternative material that can be made from a low cost, renewable resource such as starch, with the following properties: transparent, biodegradable and compostable, suitable for thermoforming and packaging foodstuffs (for example: dry foods) and with comparable production costs to oil-based plastic materials.

4. To carry out a Life Cycle Assessment (LCA) to evaluate the environmental profile of biopolymers versus oil-based polymers through the supply chain, production, use and final waste disposal options. The data obtained from the LCA will be assessed from an environmental perspective, highlighting hotspots to be improved on and providing valuable production, use and waste information. The LCA will address the simplistic pyramid classification system provided by the environmental group Green Peace, either supporting or contesting its environmental classification on polymers.
   The LCA is intended to provide an assessment of the environmental characteristics of packaging materials made from oil-based polymers (PVC & APET) and non oil-based polymers (PLA and novel starch-based formulations produced by the RE at Brunel University) and to evaluate the current and projected environmental impacts arising from the manufacture, use and disposal of these polymers. The overall goal of the LCA is to environmentally compare oil-based and non-oil based polymers, conclude which of these two material types is more environmentally sustainable for the packaging industry and identify which disposal route is best for each polymer.

5. To determine the extent of biodegradation that may occur when bio-based or biodegradable packaging materials are disposed of under a simulated domestic (home) composting regime. The main aim of the study was to establish which of a range of potentially biodegradable packaging materials would show levels of biodegradation appropriate for disposal at their end-of-life via home composting together with green garden waste. Biodegradation was assessed by material weight loss over a 24 week winter/spring period between November and May in the South East of the UK. The studies were conducted on both small samples and complete packaging/food service items. Additional research was conducted to determine whether it is possible to link the simulated domestic composting regime to a laboratory scale version, which has advantages such as a shorter time scale, less specimen material requirement and the ability to control the experimental conditions.

The research assessed the need for specific identification and labelling of biodegradable packaging materials that are suitable for home composting.

1.3 Research methods and main results

This section summarises the research methods and main results from the research project carried out as part of this EngD programme and presented in detail in the following chapters of this portfolio.

1.3.1 Approach and methodology

The research project draws together 5 different streams of investigation, all of which evolved from an initial objective to develop a novel starch-based material that would satisfy functional, economic and environmental requirements. An "as-is" examination of the food packaging industry gave rise to two broad areas of consideration: "Process" and "Product".

Under the umbrella of "Process", current manufacturing and disposal practices were assessed both from the perspective of Pactiv, the sponsoring organisation, and from the perspective of the industry as a whole.

Within the "Product" domain, the required specifications and properties for food-packaging materials were examined as well as the nature of existing starch-based polymers compared to conventional oil-based materials.

Bringing these two elements together culminated in five projects that validate the hypotheses elaborated in the as-is assessment, develop a thorough and practical insight into the feasibility of suggested future practices and contribute to the knowledge and understanding of these increasingly important issues:

- Reduction of environmental impact from Pactiv's production
- Potential biodegradable alternatives to oil-based polymers
- Development of novel starch-based materials
- Comparative LCA of biopolymers and oil-based polymers for food packaging
- Domestic composting of biodegradable polymer packaging materials

Each sub-project was developed within a defined framework or methodology:

1.3.1.1 Reduction of Environmental Impact from Pactiv's Production (Chapter 4)

Current manufacturing and disposal practices were assessed both from the perspective of Pactiv, the sponsoring organisation, and from the perspective of the industry as a whole in order to identify hotspots for improvements. As a result, five sub-projects are identified to develop a thorough and practical insight into the feasibility of suggested future practices:

- An analysis ("SWOT": Strengths, Weaknesses, Opportunities and Threats) of the environmental pressures facing Pactiv and its ability to respond to these whilst maintaining its market leadership
- A systematic evaluation of Pactiv's manufacturing processes and potential adaptation to meet new demands
- An assessment of the functionality, performance and commercialisation of the technology in the food industry
- An examination of Pactiv's financial accounts to identify areas for cost reductions around inputs to the manufacturing process (raw materials, semi-processed materials, packaging, storage etc) and waste disposal

1.3.1.2 Potential Biodegradable Alternatives to Oil-based Polymers (Chapter 5)

Within the range of products in Pactiv, the required specifications and properties for food-packaging materials were examined in order to compare conventional oil-based materials with potential biodegradable alternatives. These include the following approaches:

- A case study to assess the existing "biodegradable"/"Sustainable" polymer materials, primarily to analyse the cost and environmental impact of the starch-based food packaging compared to other types of biodegradable polymers and oil based polymers
- Sourcing of materials for comparison tests
- Characterisation of the mechanical and physical properties of sample materials in order to asses the functionalities
- Lab-scale experiments into extrusion and vac forming
- Comparison of the mechanical and physical properties of sample materials by extrusion trials and characterisation of the materials
- Industrial trials to thermoform suitable materials

1.3.1.3 Development of Novel Starch-based Material (Chapter 6)

A preliminary study was carried out to prove the feasibility of developing a low-cost starch-based sheet material for thermoforming food packaging trays. This included the following elements:

- A literature review of existing research material on biodegradable polymers and thermoplastic starch
- Development of novel starch-based packaging on a laboratory scale at Brunel University
    - Established the baseline formulation of the materials based on previous work at Brunel
    - Optimised physical and mechanical properties of the materials, by careful selection of starch, plasticizers, additives and processing conditions
    - Studied the effects of key additives on the mechanical and physical properties by extrusion trials and characterisation of the materials
- Benchmarking this novel starch-based material against commercially available and functionally comparable biodegradable and oil-based packaging polymers

1.3.1.4 Comparative LCA of Biopolymers and Oil-based Polymers Suitable for Food Packaging (Chapter 7)

The methodology for the project will be based on the ISO 14040 series of international standards for LCA. This methodology is very detailed and will be covered in Chapter 3 together with a thorough examination of the background to LCAs

- Specific objectives for carrying out the LCA include:
    - Contribute to knowledge of the environmental impacts of waste disposal of Biopolymers
    - Collect significant environmental data on the waste plastic stream
    - Identify the most environmentally friendly waste disposal option for examples of both petroleum and non-petroleum based polymers
    - Assess the influence that sustainable waste management has upon the whole life cycle of the product. This will provide information to manufacturers such as Pactiv on the importance of using polymers, which have a lower environmental footprint and more sustainable end of life

- The goal was to provide an objective assessment of the environmental characteristics of packaging materials made from oil-based polymers (PVC & APET) and non oil-based polymers (PLA and novel starch based formulations produced by the RE at Brunel University) as well as to evaluate the current and projected environmental impacts arising from the manufacture, use and disposal of these polymers.

- The methodology used was based on the ISO 14040 standards.

- The case study was based on Pactiv's Café Revive sandwich packs. PVC and APET trays were compared to PLA and novel starch trays.

- The LCA was based on a 'cradle to grave' basis from raw material manufacture to final disposal with several waste disposal options being examined.

- The functional unit used was '1000 Café Revive Sandwich Packs at the consumers, with disposal.'

- The reference flow allowed for losses in the system

1.3.1.5 Home Composting of Biodegradable Packaging Materials (Chapter 8)

A composting study in a simulated domestic composting environment was carried out to assess the biodegradability/ compostability of a range of materials claiming to be compostable. The design of the tests followed EN 13432 standard taking the following approaches:

- Defined research objective
- Carried out research into biodegradable materials
- Sourced commercially available materials that claimed to be biodegradable
- Sourced equipment and suitable herbaceous materials
- Set up composting project
- Periodically extracted and evaluated samples of composted material
- Analysed and presented results

1.3.2 Main Results

- The environmental impact of the food packaging industry is of increasing concern to governments, environmental organisations and consumers. The market for biodegradable packaging is expanding rapidly but is still in its early stages of development, predominantly due to a lack so far of suitable materials (that meet all environmental, mechanical, physical and economical requirements)

- A proliferation of thought leadership and research into packaging materials exists. The domain of biodegradable polymer materials is still not deeply understood and much of the research is currently ongoing and therefore has yet to be fully documented. The information that does exist tends to be disseminated by pressure groups and as such public understanding is heavily influenced by fairly radical viewpoints. Furthermore, the majority of published materials focus on packaging materials themselves rather than the end-of-life options so the market coverage is very unbalanced

- Although Pactiv is a market leader in the food packaging industry, it is facing increasing pressure to reduce its environmental footprint whilst remaining cost competitive and at the forefront of product innovation. By focussing on back end operations as well as productivity, £1m in cost savings were achieved by changing working practices: In the first instance, by re-using materials that were previously considered to be waste, Pactiv reduced its requirement for raw materials. Secondly, re-processing materials that were of no use to Pactiv but could still be used for lower grade applications in other industries established a new revenue stream.

- Of all the "biodegradable" and "sustainable" materials tested, PLA was found to be the most suitable for food packaging use in terms of physical and mechanical properties as well as processability with existing technology. However there are two obstacles to making PLA commercial in the UK: Firstly, PLA is predominantly manufactured from genetically modified corn. Secondly, despite outward support from consumers, in reality they are generally not prepared to absorb the higher costs implicated by the use of this material in lieu of cheaper oil-based substitutes. Manufacturers in an industry where margins are already under considerable pressure cannot sustainably transition to using such materials if they are unable to pass the higher costs onto the consumer.

- A novel starch-based tray with suitable physical properties was successfully manufactured on a laboratory scale. However, mechanical testing showed that more work needed to be carried out into the necessary additives to improve mechanical strength.

- The LCA concluded that out of all the polymers tested, PVC ranks the worst in terms of environmental profile. The novel starch performed very well. PLA performed well but energy consumption of its manufacture was high.

- The home composting trial demonstrated that a number of packaging materials that will typically biodegrade well in industrial high-temperature composting systems failed to biodegrade under a low temperature home composting environment.

1.4 Original Contribution to Knowledge and Publications

The particular aspects of the work that are original contributions to knowledge include:

- Processing a low cost thermoplastic starch material suitable for the extrusion and vac forming of a packaging tray on a laboratory scale.
- Whereas previous work has investigated industrial composting, no data existed for domestic composting. This project showed that the majority of the materials deemed "biodegradable" do not in fact decompose under low-temperature home composting conditions. Furthermore, this project revealed that biodegradable materials fall into 3 categories: Fast, medium and slow degraders.
- A laboratory-scale version of the domestic composting trial was devised. This showed that lab-scale results correlate to domestic-scale results. As such, the biodegradability of materials can be assessed on a lab-scale and the results used to predict the results of domestic composting. This is not only more efficient - on a lab-scale there is less specimen material requirement and conditions can be controlled - but enables the method to be used commercially to enable faster assessment of new materials.
- The plethora of polymer materials with vastly differing properties on the market makes disposal choices confusing and difficult, especially for consumers. The LCA highlights which end of life scenario is most suitable for each of the polymers tested.

1.4.1 List of publications

The research carried during this EngD programme has been submitted for publication in peer-reviewed journals.

1. Davies G, Murphy R and Song J. (XXXX) ***Assessment of Biodegradable Packaging Materials under Simulated Home Composting Conditions***, submitted to Polymer Degradation and Stability on October 2006.

1.5 Commercial Application - Benefits to the Sponsoring Company

As a direct result of this project, the sponsoring organisation Pactiv benefited from significant costs savings and improvements to its manufacturing process, including more efficient material consumption, reduced volumes of waste and improved working practices. This enabled them to improve their competitive positioning and secure their continued market leadership. The development of new biodegradable materials will give Pactiv the potential to exploit new and high value-added market opportunities.

The cost saving projects reduced the amount of virgin material purchased for packaging applications, by increasing the volumes of rework used. The reduction in the amount of factory waste sold on for lower grade applications rather than going into skips reduced the amount of material going to landfill and added a new revenue stream.

The use of biodegradable materials reduces the reliance on materials such as PVC, replacing it with a more environmentally friendly film for packaging, which results in a reduction in waste ending up in landfill.

The LCA provided Pactiv with an assessment of the environmental characteristics of packaging materials made from oil-based polymers (PVC & APET) and non oil-based polymers (PLA and novel starch-based formulations produced) and an evaluation of current and projected environmental impacts arising from the manufacture, use and disposal of these polymers.

The composting projects established which potentially biodegradable packaging materials show levels of biodegradation appropriate for end-of-life disposal by domestic composting with green garden waste.

All of the considerations discussed above will impact Pactiv's future business and materials strategy.

1.6 Structure of Thesis

Chapter 1: Executive summary

Background to the project
Research objectives
Approach and methodology
Main research results
Contribution to knowledge and publications
Commercial application of the research

Chapter 2: Introduction to "Environmental Packaging" and the Packaging Industry

The concept of packaging
Overview of the packaging industry
The environmental challenges for the packaging industry
Commercially available biodegradable materials
End of life scenarios

Chapter 3: Literature Review

Summary of published literature by topic area;
- Packaging materials & packaging industry
- Environmental packaging

Background to LCA and its methodologies

Chapter 4: Reduction of Environmental Impact from Pactiv's Production

Introduction to Pactiv and its environmental concerns
Pactiv's manufacturing process
Overview of inputs and outputs
Improvements to Pactiv's manufacturing process
Reduction of Pactiv's environmental burden

Chapter 5: Potential Biodegradable Alternatives to Conventional Polymers

Technical assessment of biodegradable polymers
Comparison with oil-based polymers
Assessment of processability of biodegradable polymers

Chapter 6: Development of Novel Starch-based Materials

The work carried out to develop a novel, colourless, starch based material, which was subsequently formed into a packaging tray.

Chapter 7: Comparative LCA of Biopolymers and Oil-based Polymers Suitable for Food Packaging

Evaluation of the environmental profile of biopolymers versus oil based polymers through the supply chain, production, use and final waste disposal options
Highlights environmental hotspots, which need to be improved upon by industry
Assesses the environmental group Green Peace's pyramid classification system

Chapter 8: Home Composting of Biodegradable Packaging Materials

Determines the degree of biodegradation that occurs when bio-based or biodegradable materials are disposed of under a simulated domestic composting regime

Assesses biodegradation by material weight loss over a twenty-four week period

Links the simulated domestic composting regime to a laboratory scale version

Bioassay report following the PAS 100 standard

Chapter 9: Conclusions and Recommendations for Further Work

CHAPTER 2 INTRODUCTION TO 'ENVIRONMENTAL PACKAGING' AND THE PACKAGING INDUSTRY

2.0 Introduction to 'Environmental Packaging' and the Packaging Industry

This chapter firstly examines the nature of packaging. It then provides an overview of the packaging industry before analysing the environmental impact, namely the growing burden of recycling and the driving forces to reduce both volumes of waste and the environmental footprint. Finally it considers the challenges for building a sustainable industry for environmental packaging, including the types of materials currently or potentially in the market, current waste disposal options and how these processes could be adapted to ensure sustainability for the future.

2.1 An Introduction to the Concept of Packaging

We tend to think of packaging as a relatively modern concept invented by mankind. However, if we take a look at the natural world, in particular the plant kingdom, this is clearly untrue. There are many examples in nature where a food product grows its own protective packaging, for example, bananas and oranges. These are excellent examples of functional, biodegradable, environmentally friendly and sustainable forms of packaging.

Today's packaging industry is founded on a sustained attempt to emulate the functionality and efficiency of such natural packaging, whilst meeting the demands of the modern consumer. Technological improvements in the quest to replicate natural packaging has led to the dominance of plastic packaging, which admittedly comes closer to the desired quality and functionality of natural forms, but lacks the biodegradability and is ultimately unsustainable in its current form. Although the focus of this study is on man-made packaging, the functions and criteria for packaging in nature still pertain. A typical definition of packaging is that "packaging must protect what it sells and sell what it protects"[1]. Packaging should therefore fulfil at least one of the following functions:

- Provide protection from physical damage, contamination and deterioration
- Give sales appeal
- Ensure the product is easily recognisable
- Display information about the product

- Optimise distribution and storage costs
- Provide consumer convenience and safety

Other important features of packaging include minimal cost, maximum convenience and recyclability. Packaging can thus be evaluated by the following criteria:

- Appearance
- Protection
- Function
- Cost
- Disposability.

Packaging can be categorised by its base materials, for example, paper, board, plastics, metals, glass and wood. The base material is chosen in accordance with a combination of factors including desired shelf-life, image, cost, suitability, usage and custom.

There are three broad types of packaging:

- *Primary packaging* is often in direct contact with the goods and is taken home by the consumer
- *Secondary packaging* is the packaging used to transport primary packaging and its contents, for example, boxes used to transport quantities of primary packaging from production to storage and to transport primary packaged goods from packer filler to supermarkets. Secondary packaging is often the largest in size of the three forms of packaging.
- *Tertiary packaging* refers to packaging used to secure large quantities of goods and aid their transportation, for example, wooden pallets and plastic wrap

On the whole, secondary and tertiary packaging materials are used in large quantities by industry and are simple in formulation. Therefore, they are relatively simple to collect, sort and either reuse or recycle. Primary packaging, however, ends up with the consumer and is often made up of a variety of polymer types, which poses problems for collection and sorting. There is also an infinite range of design possibilities, such as boxes, bags, bottles, pouches, cartons, cans, trays, closures, lids and caps. Sizes range from miniature to extra large; shapes range from the conventional to custom designed, and all the colours of the spectrum are used for printing and decoration. There are also more specialist types of packaging, which include biodegradable, tamper evident, child proof and anti counterfeit varieties [2].

This project will focus on primary packaging as opposed to secondary or tertiary packaging.

2.1.2 Trends in the Packaging Industry

Society today has developed in such a way that packaging is now a £300 billion per annum global industry expanding at a rate of 12% annually [3]. Almost everything we purchase is packaged in one form or another and this packaging typically accounts for 5 % of the final selling price of an item [1].

The driving forces behind these trends are customer requirements for higher levels of *quality*, *variety* and *convenience* combined with changing demographic characteristics.

- *Quality:* An example where packaging has been used to create the image of quality is in the use of the "step-can" for the selling of traditionally canned fruit[4]. 'Step-can' is a transparent plastic PET can with an aluminium ring pull top and solid aluminium base. When consumer tested, results showed that affluent members of the public were prepared to pay up to three times the original price for canned fruit in the new packaging. This was attributed to a lack of trust in the unseen fruit inside the tin can. This new can allows the consumer to see what they are buying. However, market research revealed that the plastic sides of the can were a disadvantage when promoting the new can in countries such as Germany and Denmark where the ability to recycle glass is preferred to any advantages offered by plastic containers. This is further reinforced when considering plastic (PET) jam jars, which have started replacing the more traditional glass jars. Consumers believe the plastic to be inferior quality to glass, despite plastic actually having the superior properties of being both light weight and shatterproof.

- *Variety:* In the late 1980s and early 1990s a noticeable change in food retailing started to take place from small individual shops such as green grocers, butchers and bakeries in local towns and villages, to large out of town supermarkets. Consumers started to shop once a week, generally travelling by car and fulfilling all major shopping requirements in one store. This had a marked influence on packaging, as consumers were offered larger economy sized packs, and more variety. Supermarkets add around 1,000 new products each year to their existing range of over 10,000 products. This in turn creates a greater demand for different types of packaging. Consumers are becoming more health conscious and actively seeking out foods which have fewer chemicals and preservatives. As a result packaging has become more technical in order to preserve food for longer. In short we are changing from a 'needs' based to a 'wants' based economy [5].

- *Convenience:* With an increasing trend towards smaller families and single person households, there has been a huge increase in the demand for convenience ready meals, particularly frozen foods [6]. This has been further encouraged by the increased ownership of microwaves. This market has helped increase sales in the packaging industry, and furthermore packaging is being developed to be more convenient to use with tamper proof seals. An example of this is squeezable bottles for ketchup. With people working longer hours and having more disposable income, there is an increased market for pre-made sandwiches and salads. The use of PVC thermoformed sandwich wedges and salad bowls has made this possible. In developed countries food packaging represents 60% of all packaging by volume [7]. This is due primarily to strict food packaging regulations, plus the drive to enhance appearance and therefore increase sales. In the UK, the proportion of food unfit for consumption before it reaches the consumer is 2%, whereas in developing countries, where packaging is not as widespread, this loss can be in excess of 40% [8].

2.1.3 The Impact of Industry Growth

The impact of this growth in the volume of packaging used each year is a corresponding growth in the volume of waste packaging material requiring disposal.

The most common types of materials used for primary packaging are: glass, metals, paper or pulp based materials and plastics. Some of these materials are easier to recycle or dispose of than others:

- Glass can be returned for re-use or recycled. Six billion glass containers are used in the UK annually and the recycling rate was about 22% [9]. The UK has an extensive recovery and recycling system for glass with over 20,000 bottle banks in operation today [7].
- The recycling rates of metals such as aluminium are high: in 1996, five billion cans of product were consumed and 31% of these were recycled [10], mainly due to a strong scrap metal value of £650 - £750 per tonne in the UK [11]. Steel, being magnetic, is easy to extract from a mixed waste stream. In 1998 31% of steel packaging was recycled [10].
- Paper has the highest recycling rate. Figure 2.1 shows the recycling rate for the UK in 2003 as 65% compared to 19% for plastic.
- Plastics packaging has become complex, with inherent difficulties in sorting for recycling, despite SPI polymer identification symbols (Figure 2.2), which are used to aid identification when recycling. This is due to coatings, printing and lamination, as well as the inclusion of additives such as fillers, plasticisers, lubrications, colours, masterbatch and antioxidants. Currently most of the sorting is done manually, which is expensive, especially in the UK where labour costs are high. Plastic packaging has a low density i.e. it is light-weight. Existing landfill reduction targets are weight based, which discourages local authorities from recycling low density and therefore light-weight plastic packaging materials. Plastics are often blamed for shortening the life of UK landfills due to their longevity, high volume and often-colourful appearance, which make them highly visible in waste streams [12]. Plastic packaging is considered by the general public to be a major source of litter that pollutes

waterways and beaches, threatens animals and marine life and is costly for local authorities to clean up [13].

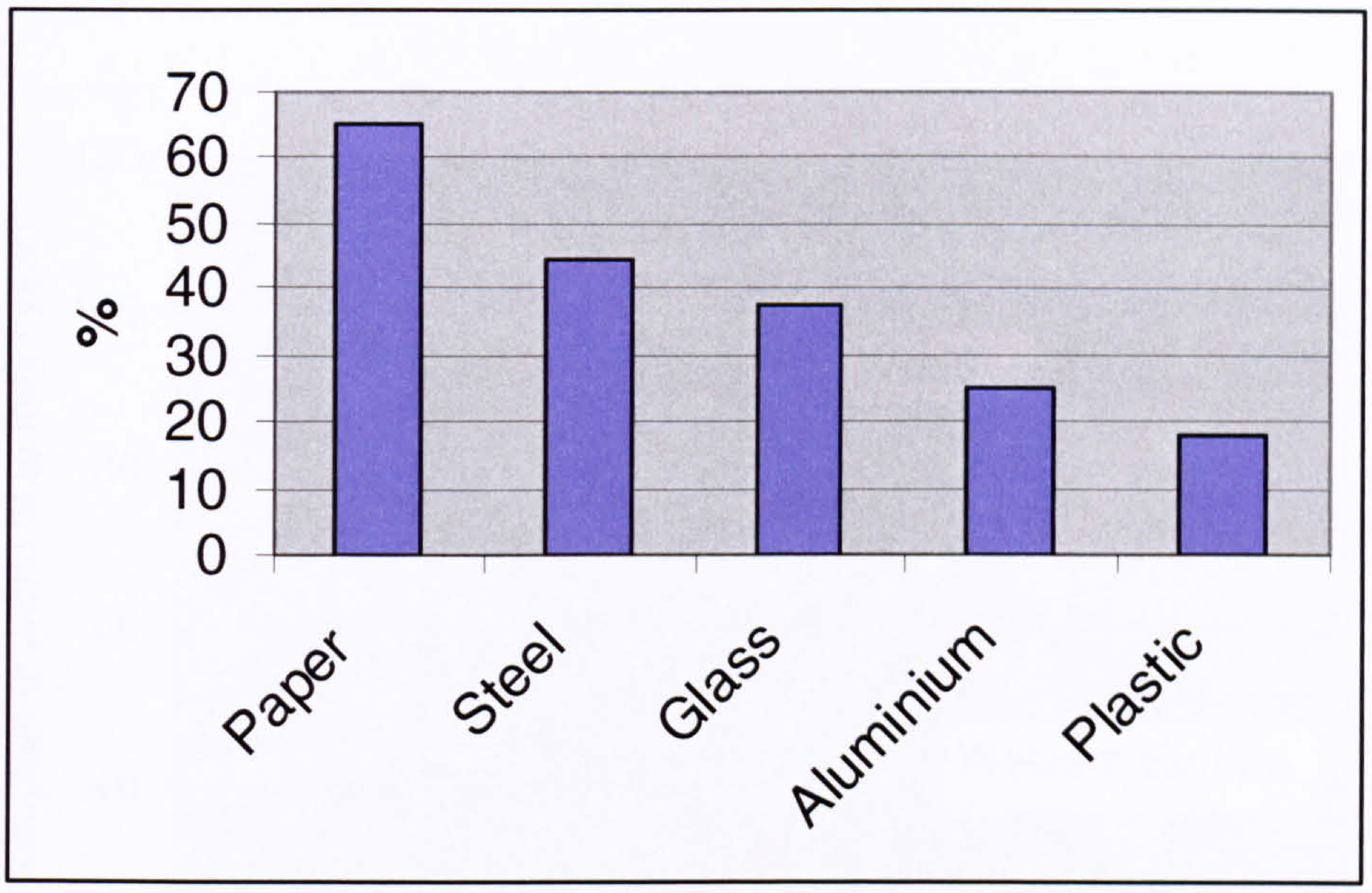

Figure 2.1: Recycling rate of packaging waste [1]

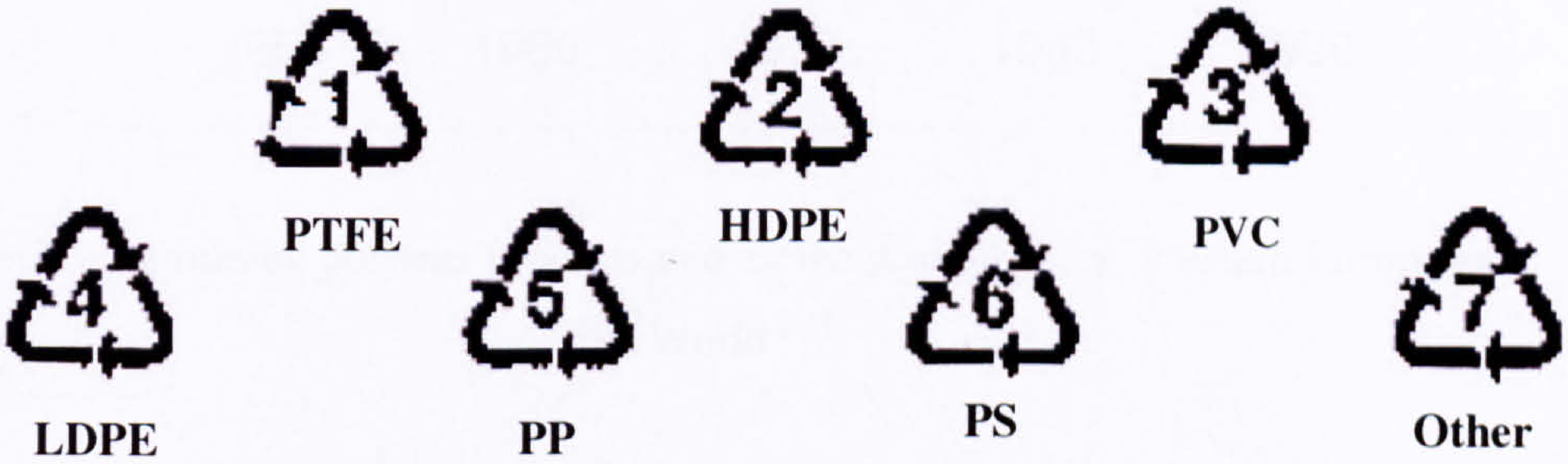

Figure 2.2 SPI polymer identification symbols, used on plastic products to aid recycling [14]

The challenges posed by this increased demand for plastic packaging and the subsequent disposal/recycling of an increasing volume of waste will be examined in more detail in the remainder of this chapter.

2.2 Polymers in Packaging

There has been a rapid increase in the production of polymers over the last 50 years as shown in Figure 2.3, and a dramatic increase in its use for packaging.

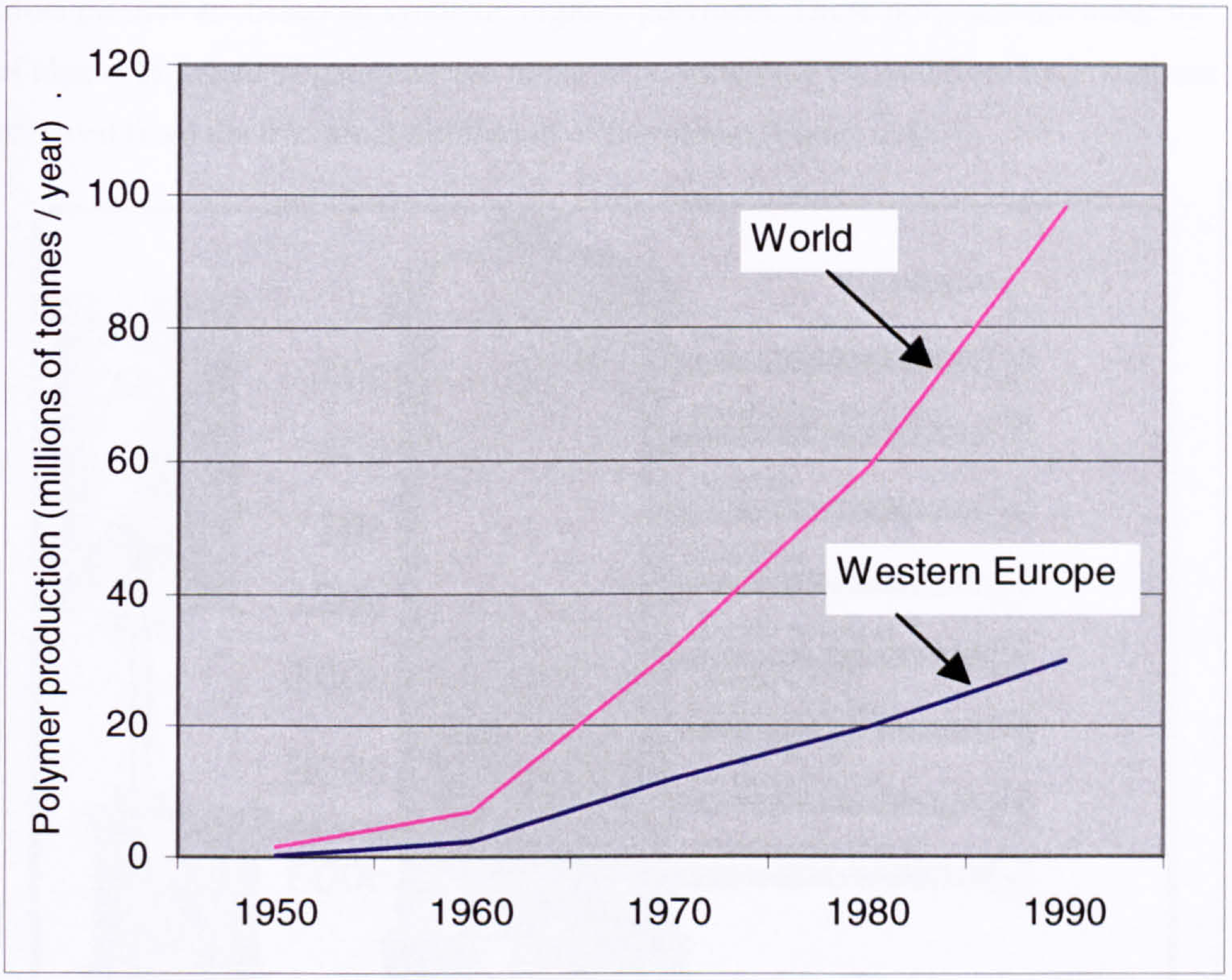

Figure 2.3: Increasing polymer production over the past 50 years, Western Europe and the World [15]

Over the past fifty years, petroleum-based polymers have been replacing traditional packaging materials such as paper, glass and metals due to their superior properties. Plastics are comparatively low cost, low density resistant to corrosion, and boast improved physical and mechanical barrier properties. Furthermore, they possess preferable optical properties and a higher speed of processing. The factors that have driven the success of these petroleum-based polymers, and now drives the demand for comparable materials that meet today's environmental needs, invariably entail a high degree of complexity in their manufacture and management, which merits deeper analysis.

2.2.1 The Composition and Manufacture of Polymers

Most plastics are based on synthetic organic polymers. These polymers are made up of chains of linked single molecule monomers, which are derived from hydrocarbons obtained from the fractional distillation of petroleum (Figure 2.4).

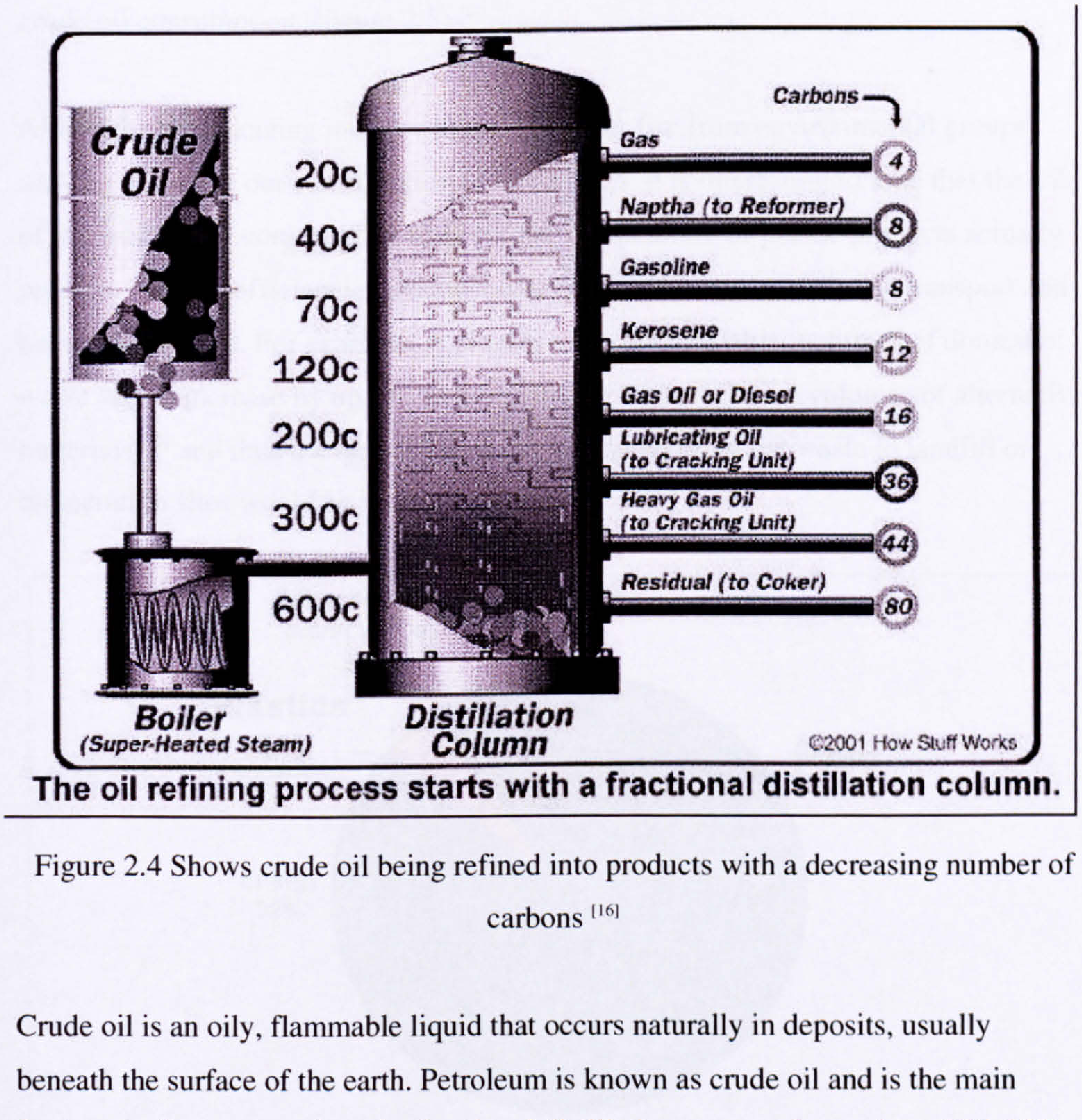

Figure 2.4 Shows crude oil being refined into products with a decreasing number of carbons [16]

Crude oil is an oily, flammable liquid that occurs naturally in deposits, usually beneath the surface of the earth. Petroleum is known as crude oil and is the main feedstock of monomers into the fractional distillation process. It consists of 95–98% hydrocarbons and 2–5 % oxygen, nitrogen and sulphur-containing compounds [17].

Fractional distillation, as depicted in Figure 2.4, separates the saturated hydrocarbons in petroleum according to weight. Smaller, lighter hydrocarbons are generally more useful and so the larger ones are often subsequently cracked to olefin mixtures, which are then re-fractioned by distillation.

The majority of the resulting compounds are used for heating, energy and transport. Some, however, are either used as they are, or converted into the desired substituted hydrocarbon monomers to make polymer plastics. As such, the polymer industry is a major petrochemical customer. Specifically, 60% of the products of the cracking process and subsequent products of naphtha, a group of volatile flammable liquid hydrocarbon mixtures, are used to produce polymers. This amounts to 4% of global crude oil consumption (Figure 2.5) [18].

Although the packaging industry has come under fire from environmental groups seeking to reduce our consumption of fossil fuels, it is interesting to note that the 4% of the world's oil consumption used for the manufacture of plastic products actually promotes energy efficiencies amongst other oil consumers, notably the transport and heating industries. For example, if plastics were not available, volumes of domestic waste would increase by up to 150%, due to the higher relative volumes of alternative materials [19] and thus the fuel requirement for transporting the waste to landfill or incineration sites would be much higher.

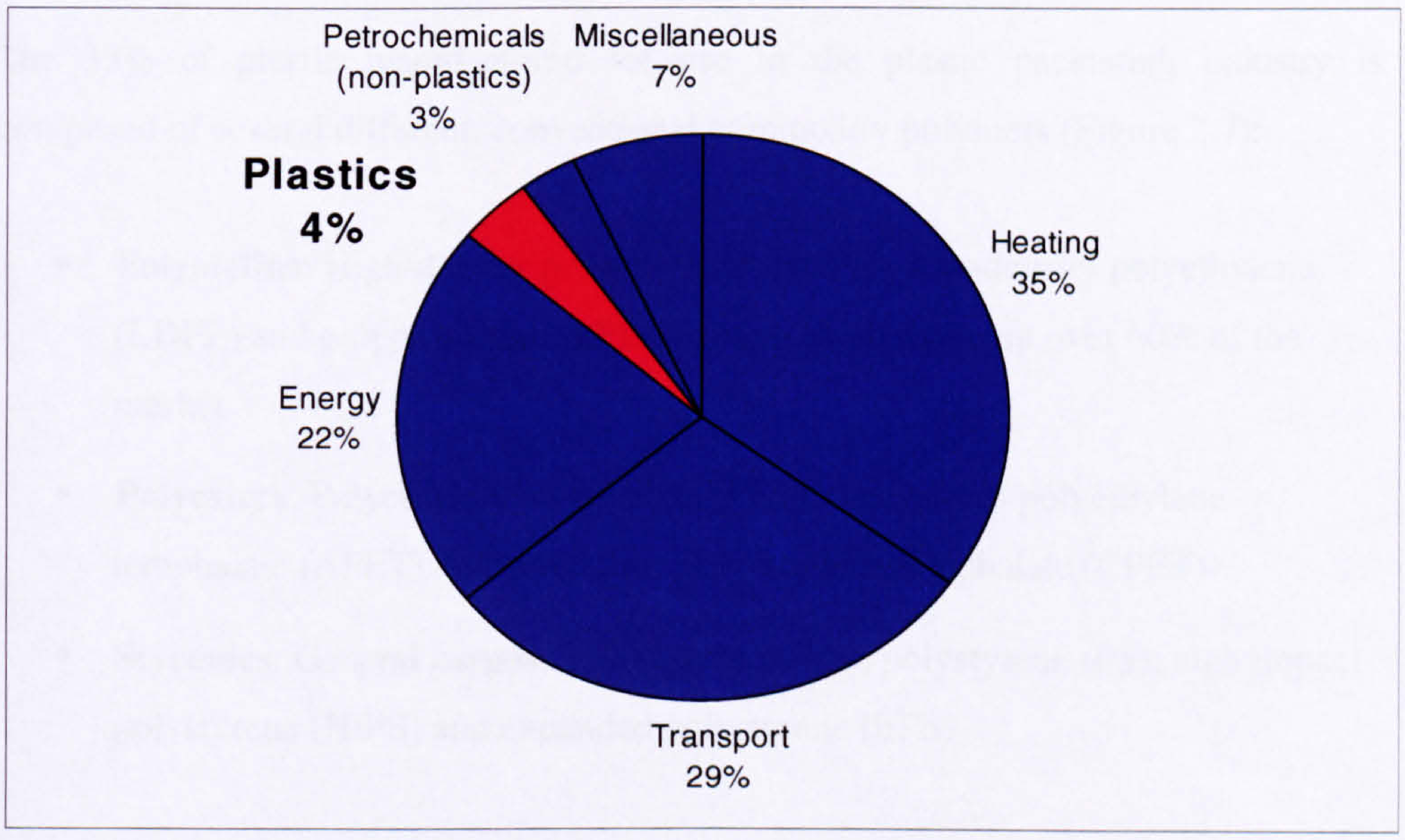

Figure 2.5: The applications of petroleum products in Western Europe 1990[18]

Of the 4% of the world's petroleum consumed in the manufacture of plastics, a third is consumed by the plastic packaging industry (Figure 2.6). In other words, the plastic packaging industry consumes 1.3% of global oil consumption.

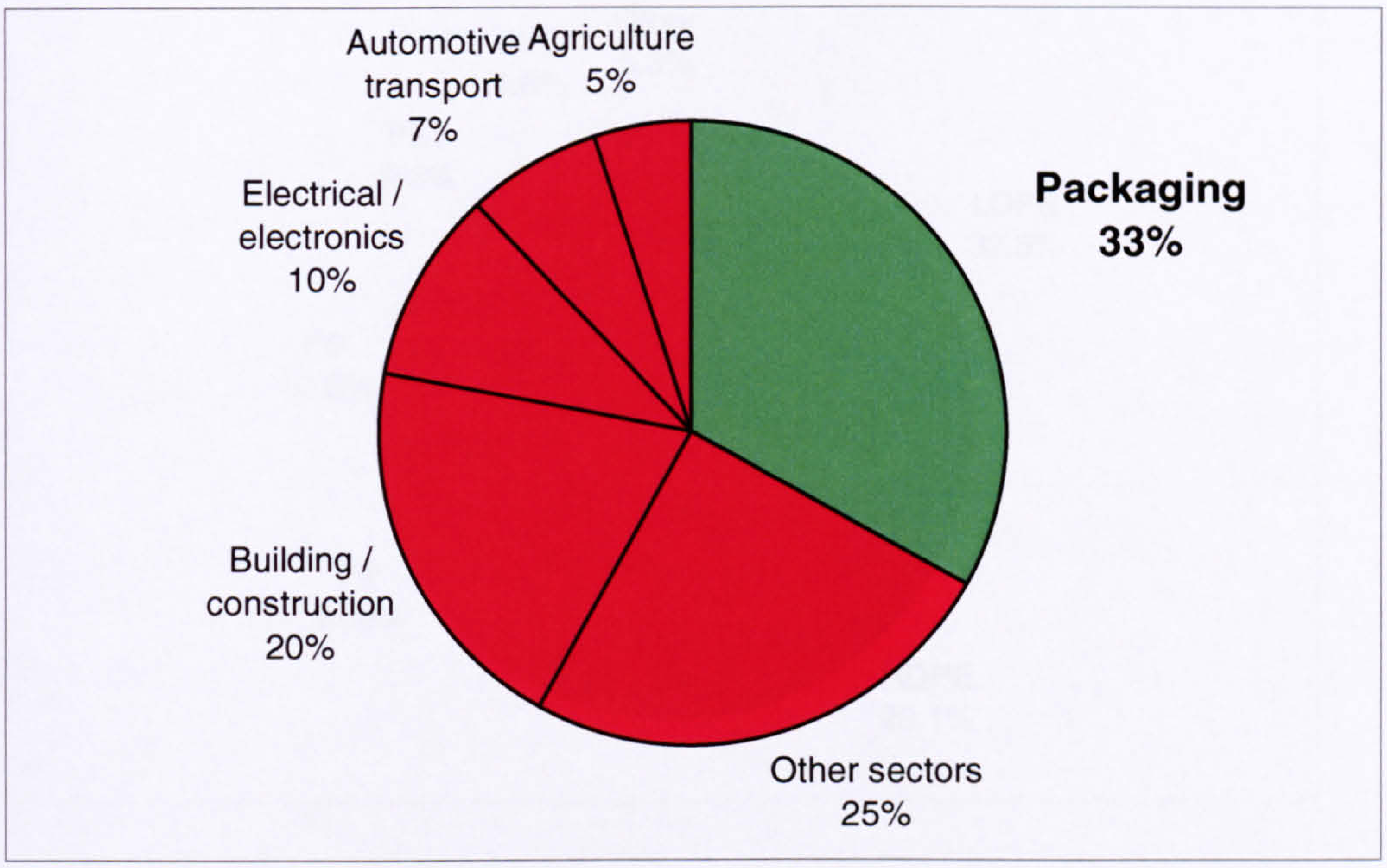

Figure 2.6: A breakdown of uses of the 4% of global oil consumption used in the manufacture of plastics [15].

The 33% of plastic manufactured for use in the plastic packaging industry is composed of several different, conventional commodity polymers (Figure 2.7):

- **Polyolefins**: High-density polyethylene (HDPE), low-density polyethylene (LDPE) and polypropylene (PP). Together these make up over 60% of the market
- **Polyesters**: Polyethylene terephalate (PET), amorphous polyethylene terephalate (APET) and crystalline polyethylene terephalate (CPET)
- **Styrenics**: General purpose polystyrene (GPS), polystyrene (PS), high impact polystyrene (HIPS) and expanded polystyrene (EPS)

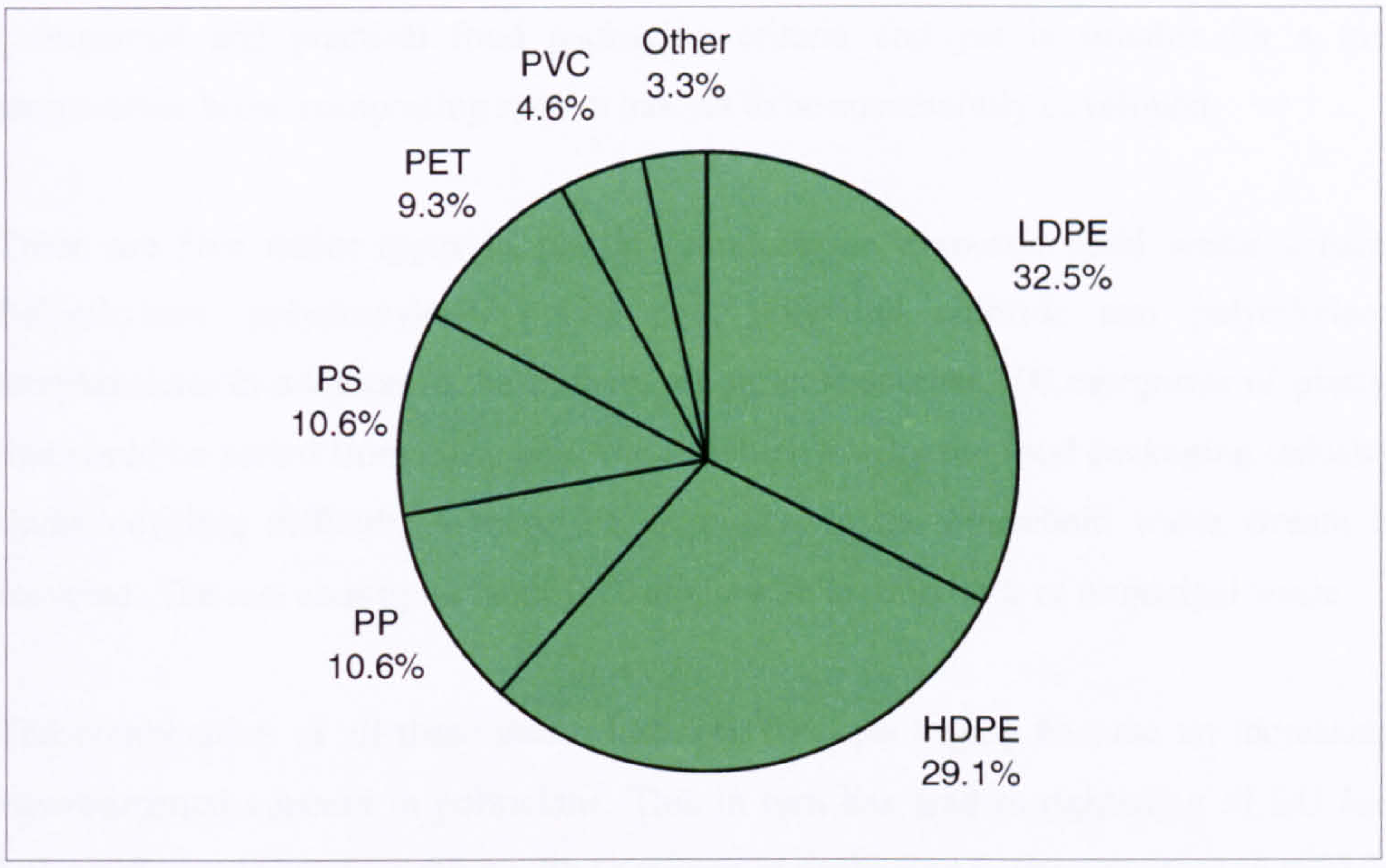

Figure 2.7: Breakdown of Plastics used in packaging [15]

2.3 The Environmental Impact of Packaging Waste

The existence of so many different types of polymer in everyday packaging poses considerably challenges for their disposal.

At the end of their useful life, waste polymers enter various waste streams. A third of all EU municipal waste generated is made up of packaging waste. This amounts to 67 million tonnes every year that ends up in the municipal solid waste stream [20]. Municipal solid waste includes household waste such as food packaging, as well as waste from commercial industry and retailers (for example, wholesalers and supermarkets). This waste stream currently attracts the largest volume of oil-based plastics, which are viewed as non-biodegradable and can be difficult to re-use or recycle if material types are mixed. Another means of disposing of waste is incineration, however UK facilities are currently running close to maximum capacity and this method is considered to be highly energy intensive as well as wasteful.

Composting is considered to be one the most environmentally friendly methods of waste disposal and has historically been used for the disposal of organic matter but is only suitable for biodegradable materials. A biodegradable polymer that satisfies commercial and practical food packaging criteria and yet is suitable for a low temperature home composting system has yet to be successfully developed.

There are five major types of plastic found in the domestic solid waste stream: Polyethylene, polypropylene, polystyrene, polyvinyl chloride and polyethylene terephthalate. In addition to these, there are at least another 100 categories of plastic that could be sorted from household waste, which is why the food packaging industry finds recycling difficult. A mere 5% of plastic in the household waste stream is recycled. The rest ends up in landfill [21] along with around 85% of municipal waste.

The combination of all these issues has seen food packaging become an increasing environmental concern to politicians. This in turn has lead to tightening of EU and UK regulations to reduce the 8 million tonnes of packaging waste produced in the UK by 50% [22]. Biodegradable food packaging materials therefore are considered to have great potential in countries such as the UK where landfill is currently the main waste management practice, to reduce the environmental impact and help meet targets imposed by the EU.

2.3.1 The Packaging Waste Directive

Discarded food packaging is an obvious source of litter and has resulted in a strengthening of European Regulations such as the Packaging and Packaging Waste Directive 94/62/EC, which is concerned with minimising the creation of packaging waste material and promoting energy recovery, re-use and recycling of packaging. The Packaging directive covers all packaging placed on the market within the EU and all packaging waste, whether disposed of at industrial or commercial sites, or from private homes. The directive requires that all packaging placed on the market must comply with essential specifications and achieve the following targets:

- Recovery: between 50 and 65%

- Recycling: between 25 and 45%, with a minimum of 15% by weight for each packaging material (glass, plastic, paper/ cardboard, metal and wood)

It is particularly difficult for the UK to meet the targets set by the directive as approximately 85% of municipal waste in the UK ends up in landfill [23]. Due to the fact that plastic packaging is lightweight and recycling targets are based on weight, efforts to recycle plastic packaging have been minimal.

2.3.2 The Management of Plastic Packaging Waste and Biodegradable Packaging

At the end of its service life, polymer waste may be managed in one of the conventional manners:

- Recycling
- Incineration
- Landfill

Composting can be considered as a new option if packaging materials meet certain biodegradability criteria. These will now be discussed together with the current levels of technical barriers, economical barriers and environmental legislations.

2.3.2.1 Recycling

The efficient recycling of plastics requires a clean, monotype, homogenous waste stream. This is possible to achieve at industry level with careful management, but post consumer primary plastics tend to be contaminated and have mixed compositions, resulting in a non-profitable recycling proposition. The UK's Government researchers have estimated that 70% of the plastic in municipal solid waste could be recycled. Current post-use plastic recycling figures look somewhat different: only 5.7% of plastic packaging was recycled in the UK in 1998 and most was from industry [7]. In 1999 this increased significantly to come into line with EU law, although very little plastic from the household waste stream gets recycled even now, and in 2001, 80% still ended up in landfill [24]. Whilst the process of polymer recycling is a relatively simple one involving processes such as granulation; shredding and bailing there are nonetheless numerous obstacles to overcome:

- Difficulties in collection, separation, and identification of plastics
- Less economically viable than virgin feedstock
- Degradation due to the repeat process
- Time consumption
- Fluctuating polymer prices
- Property downgrading due to contamination or combinations of polymers

The situation may change as environmental legislation tightens and if oil prices continue to soar. The technologies available for recycling petroleum-based plastic packaging waste may regain attention. These technologies include [25]:

- The integrated collection of household waste for energy recovery using advanced incineration technology
- The separation of high-calorific value plastics from household waste for use in cement kilns thus reducing the need for coal, another fossil fuel derivative
- The separation of plastics from household waste and their use as a reducing agent in blast furnaces or for materials feedstock recycling
- The separate collection, sorting, cleaning, and mechanical recycling of plastics [26]

2.3.2.2 Incineration

Approximately 40 million tonnes of municipal solid waste are incinerated in the EU annually with 95% energy recovery [27]. Incineration with energy recovery of heat is a viable option once it is no longer possible to reuse or recycle materials. Exceptions to this include polymers containing chlorine such as PVC (polyvinyl chloride), which is an environmental and human hazard if burnt at low temperatures, due to the toxic chlorine compounds emitted. The advantages of burning plastics include the lack of sulphur and nitrogen given off, unlike traditional alternatives such as coal, and reduced acidification of the atmosphere [28]. The incineration of used and contaminated petroleum-based plastics could therefore be considered the most efficient way of gaining maximum benefit from the petroleum as it is possible to recover almost the same amount of heat from the plastic from the same amount of petroleum [29].

However, current incineration facilities are running close to maximum capacity and are often criticised as being a highly energy intensive solution.

2.3.2.3 Landfill

Landfill has been used as a cheap means of disposal for many years in countries such as the UK and is still the main end-of-life route for municipal packaging waste, including plastics. This is mainly due to the difficulty and cost of sorting and transporting large volumes of light-weight mixed and contaminated plastics, but as landfill sites become scarce, the whole idea of landfill is being seriously questioned.

The landfill of traditional petroleum based plastics could be seen as wasting the energy potential of the petroleum contained within the plastic. For example in 1999, Western Europe sent 8.4 million tonnes of plastics from the municipal waste stream to landfill [28]. In 2001, over 423,000 tonnes of plastic bottles were sent to landfill [30]. However, the land filling of traditional petroleum based polymers is preferred to the land filling of biopolymers because they are more stable materials, reduce the risk of pollution and allow the landfill site to stabilise more quickly than organic and degradable materials. This in turn allows quicker site redevelopment. The Landfill Directive (99/31/EC) aims to reduce the amount of biodegradable municipal waste, including biodegradable packaging going to landfill by 35% of the 1995 total by 2020.

2.3.2.4 Composting and Biodegradable Packaging

Historically, composting is used for treating 'green wastes'. However the process of breaking down compostable/ biodegradable waste materials is also the preferred route for waste management of compostable/ biodegradable packaging waste [31].

Improved recycling methods of commodity plastic materials have helped to accomplish the goal of waste reduction. There are end-use applications, however, where product and materials recycling is neither practical nor economically feasible.

Examples tend to include heavily contaminated lightweight items such as rubbish bags and disposable products such as food packaging. These are prime examples of where materials that would break down (biodegrade) under a wide variety of environmental conditions, including composting, would be beneficial. Figure 2.8, shows the possibilities for achieving both waste reductions and improved waste management using natural biodegradable plastics.

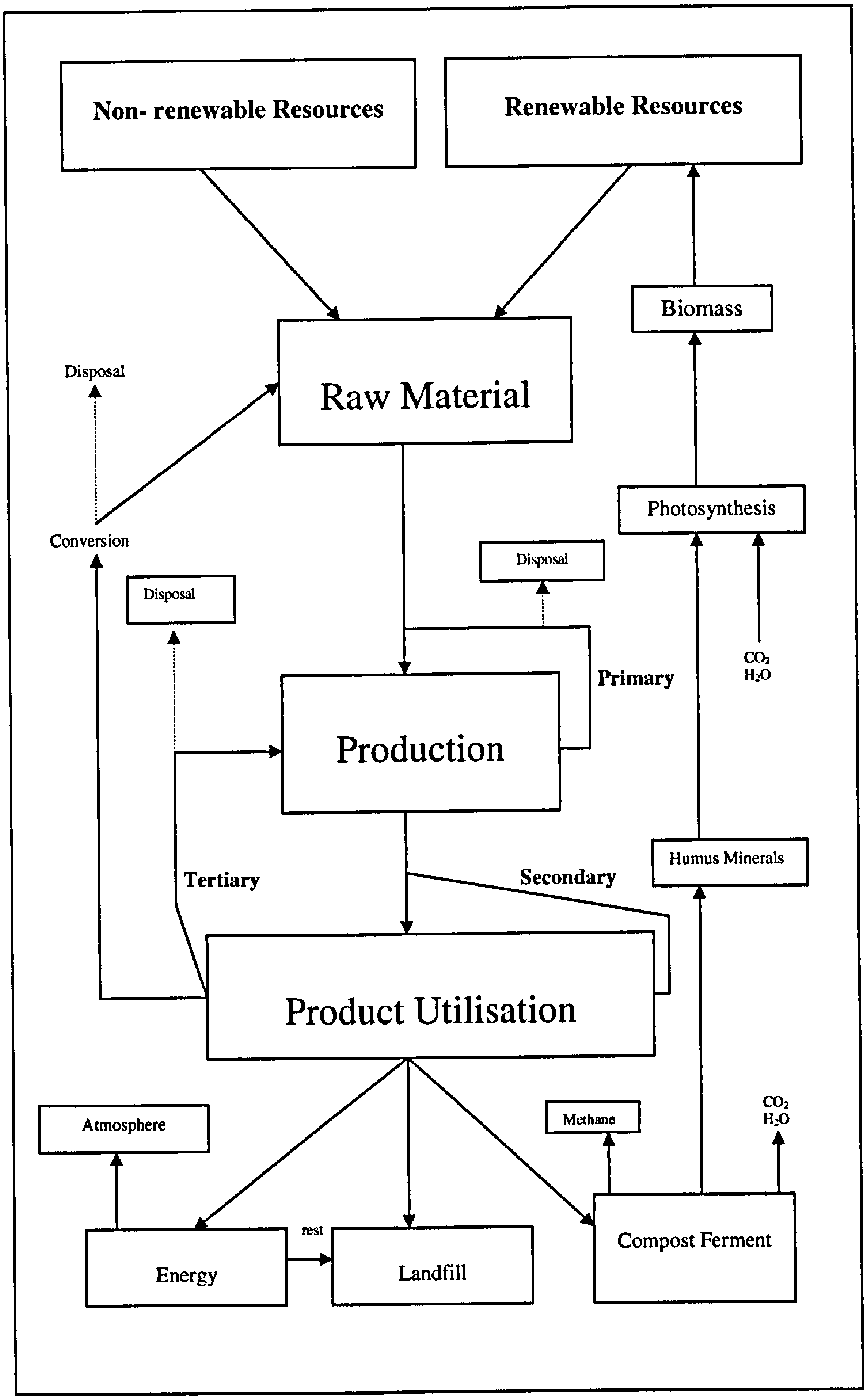

Figure 2.8 Potential disposal routes for waste.

A definition of biodegradation given by the CEN (European Committee of Standardisation) reads "A biodegradable material is called biodegradable, with respect to specific environmental conditions, if it undergoes biodegradation to a specific extent within a given time measured by standard test methods and biodegradation is a degradation caused by biological activity especially by enzymic action leading to a significant change of the chemical structure of a material" [32].

The break down of compostable materials can occur in a biodegradable process by:

- Macro-organism biodegradation, where invertebrates and insects consume the digestible ingredients such as starch in the compostable materials
- Micro-organism biodegradation by enzymes produced by bacteria or fungi
- Biodegradation occurs when micro-organisms begin growing on the surface of the polymer, digesting the small fragments of the macromolecules, which cause the secretion of enzymes that break down the polymer [33].

The degradation process can be accelerated by:

- Oxidation i.e. chemical breakdown, and/or;
- Photo-oxidation i.e. by sunlight.

Most petroleum based plastics are resistant to biodegradation; however, biodegradable polymers, such as polysaccharide, starch, polylactic acid (PLA), polycaprolactone (PCL), polyhydroxybutyrate (PHB), polyvinyl alcohol (PVOH), and chemically modified plastics, which contain starch, such as Materbi [33][34] have degrees of biodegradability. During the last decade, polymers obtained from renewable resources have attracted increasing attention, mainly due to their environmental image and potential for sustainability.

Biodegradable packaging materials can be placed into two main categories: biodegradable polymers and biopolymers. The main difference between them is their basic building blocks.

- *Biodegradable polymers* are similar to traditional petroleum-based polymers because they are synthetic and have degrees of biodegradability. Examples include PCL, PHB and PVOH
- *Biopolymers* are naturally occurring long-chain molecules such as cellulose, polysaccharides, proteins and DNA, and/or materials made from or derived from these natural polymers, and unlike synthetic polymers most biopolymers are biodegradable

The methods of degradation vary from microbiological and hydrolytical, to degradation caused by additives that catalyse the breakdown of the polymer chains [35][36]. It would be a desired feature that this degradation does not occur during the lifetime of the product but only once the end of its useful life has been reached. The biodegradation process depends on several factors, for example, the microbial activity of the immediate environment, the surface area of the polymer, the temperature, the pH, the molecular weight and the crystallinity of the polymer. The mineral structure of the surrounding environments also influences the rate of degradation, for example, anaerobic conditions occur when the compost has a compact structure, resulting in a slower rate of degradation. The rate is therefore primarily affected by the polymeric substrate, the polymer's environment and the associated organisms.

Treatment technologies for degradable and biodegradable polymers include domestic composting and municipal composting, often in vessel, a sterilisation process, due to being contaminated with foodstuffs [28].

2.4 The 'Environmental Packaging' project

This research project was initiated for a variety of reasons, including pressure from the UK government and the Packaging Directive from the EU. This meant that Pactiv had to rethink their materials strategy for the future of the packaging business.

Various opportunities were identified, namely sustainable biodegradable materials, which are less open to attack from pressure groups such as Green Peace on environmental grounds. Green Peace has been campaigning against the use of chlorine for many years now and their hit list includes: PVC (Polyvinyl chloride), PS (polystyrene), PET (polyethylene terephthalate and finally polyolefins such as: PP (polypropylene), LDPE (low density polyethylene), HDPE (high density polyethylene) all of which are used by the packaging industry and Pactiv. Green Peace prefers biodegradable polymers (from sustainable resources), but ultimately they would like reusable packaging or no packaging at all, neither of which are currently viable options in today's market.

Pressures such as these have affected Pactiv's big customers such as Marks & Spencer who have made it publicly known that they wanted to stop using PVC packaging by the end of 2002. Pactiv therefore have an invested interested in making biodegradable polymers commercially viable.

Key to the research was identifying low-cost materials from sustainable resources, which could be processed easily and meet current food packaging requirements. Biodegradable materials need to be either cost competitive with current materials or there needs to be an increase in markets such as organic markets, which would be prepared to pay the extra cost of the environmentally friendly packaging. By contrast various studies [37][38] have shown that oil-based packaging materials (all of which Green Peace are campaigning against) are in fact economically efficient. This is due to high production rates, which reduces manufacturing time and lowers the overall requirement for energy. Oil-based packaging is also environmentally efficient due to low material usage in production, for example, when thermoforming light-weight packaging. The life-cycle assessment carried out confirms whether oil-based plastics are more or less environmentally sustainable than biodegradable plastics.

Investigations carried out in Pactiv's 3 main manufacturing sites in the UK have shown that there is scope to reduce oil-based material waste going to landfill. Therefore, in conjunction with research of biodegradable materials, current manufacturing processes and materials were investigated with a view to making them more efficient, minimising cost and reducing the requirements for materials manufactured from non-renewable resources. This in turn reduces the impact on the environment.

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CHAPTER 3: LITERATURE REVIEW

3.0 Literature Review

Chapter three is a literature review, including a packaging material overview, a detailed review on conventional commodity and biodegradable polymers used in food packaging. Chapter three also includes a background to Life Cycle Assessment (LCA) and the LCA methodologies used.

3.1 Packaging Material Overview

The global packaging industry is worth approximately £300 billion per annum and has maintained a high growth rate at 12% annually [1], which reflects the requirements with improved standards of life in the modern society. Fast-paced, high food hygiene standards, greater disposable income and increasing desire for convenience are among the key factors that drive the continued growth in the packaging industry.

The UK market accounts for £9 billion [1]. It is estimated that the annual consumption of packaging materials per capita in the UK is 160kg, of which 25kg is plastic [2]. Table 3.1 shows the consumption of materials in the UK categorised into the type of materials used.

Table 3.1: Consumption of material categorised into material types, UK[1]

Sectors in Materials	£ billion	%
Paper and Board	4.2	45.5
Plastic	2.9	31.3
Metal	1.1	11.8
Glass	0.6	6.4
Wood and Other	0.5	5.0

Of all the packaging materials, paper and cardboard constitute the largest proportion of packaging materials in the UK, approximately 45% [3]. This is due to their ease of use, low cost, light-weight, high strength to weight ratio and ease of printability and recycling.

Metals constitute 12% of the UK packaging market. Aluminium is most commonly used as material for beverage cans, foils and laminates. Steel is widely for packaging of food, beverage and industrial goods such as paint and aerosols.

Glass constitutes 6% of the UK packaging market. Glass is most commonly used as material for bottles, jars, deodorant rollers and perfume jars.

Polymers constitute 31% of the UK packaging market. Packaging is the largest single use for plastics, accounting for approximately 50% of the polymers produced worldwide [3].

The considerable use of plastics is due to the beneficial properties of plastics, such as:

- Extreme versatility and ability to be tailored to meet very specific technical needs
- Light weight when comparing them to competing materials, which in trun reduces the fuel consumption during transportation
- Extreme durability
- Resistance to chemicals, water and impact
- Good safety and hygiene properties for food packaging
- Excellent thermal and electrical insulation properties
- Relatively inexpensive to produce

So in the short term at least one could say that plastic is set to stay.

There are downsides to plastics, the production and use of plastics has a range of environmental impacts. Plastic production requires significant quantities of non-renewable resources, fossil fuels, both as a raw material and to deliver the energy required for manufacturing. Plastic manufacture also requires other resources such as land, whilst producing waste and emissions.

3.2 Conventional Commodity Polymers for food packaging

Conventional commodity polymers used for packaging include:

1 PETE

- **Polyesters:** Polyethylene terrathalate (PET) Amorphous polyethylene terrathalate (APET) and Crystalline polyethylene terephalate (CPET). Example of types of packaging: Fizzy drink bottles and water containers, some waterproof packaging and oven-ready meals. Recycled PET is primarily used in textiles such as carpets, other uses include: being spun into fibre for filling pillows, quilts and jackets and recycled back into bottles.

- **Polyolefins.** High-density polyethylene (HDPE), low-density polyethylene (LDPE) and Polypropylene (PP).

2 HDPE

HDPE examples of types of packaging include: milk, detergent and oil bottles; toys and plastic bags. Recycled HDPE is used in plastic pipes, lumber, flower pots, rubbish bins or is formed back into non-food grade bottles.

4 LDPE

LDPE examples include many plastic bags, shrink wrap. Recylced LDPE is used in plastic rubbish bags and carrier bags, plastic tubing, agricultral film and plastic lumber.

5 PP

PP examples include refridgerated containers, micorwave meal containers some bags most bottle tops, some carpets and some food wraps.

- **Styrenics.** General purpose Polystyrene (GPS), Polystyrene (PS), High Impact Polystyrene (HIPS) and Expanded Polystyrene (EPS).

6 PS

PS is often used in throw-away utensils, meat and fish packaging yogurt pots, hamburger boxes, egg cartons, vending cups and protective packaging for electronic goods and toys .

3 V

- **Vinyls:** Polyvinyl chloride (PVC).

PVC is often used in food wrap, vegetable oil bottles and blister or thermoformed food packaging[4].

7 Other

- **Other Plastics:** Those which do not fall into any of the above categories.

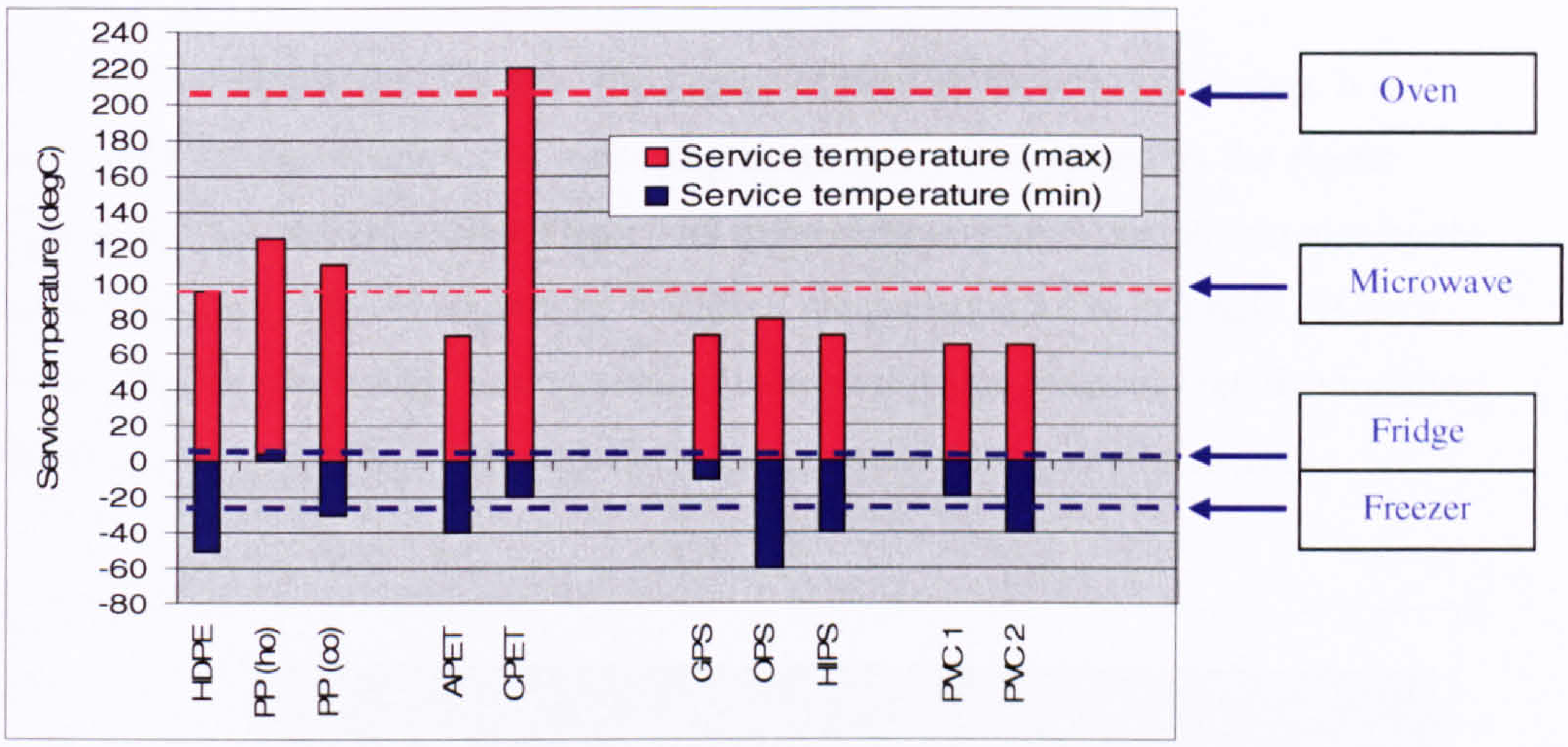
An example is melamine, which is often used in plastic plates and cups.

3.2.1 Food Compatibility

Commodity plastics such as those in figure 2.7 are required to be compatible with the majority of food contact applications when used for food packaging. Migration tests [5] are used to verify against standard test solution for specified temperatures and time intervals. Polystyrene is the most susceptible to attack by oils and therefore needs transit trial evaluations before use with food packaging. Polypropylene has the highest level of chemical resistance and is the least likely to be affected by food products.

3.2.2 Temperature Resistance

Plastic food packaging may be required to perform at various temperatures. Figure 3.1 illustrates the service temperatures for some of the plastic food packaging materials. It demonstrates that it is very important to know the intended purpose of the packaging. If the wrong type of polymer is used then the packaging could fail in its service environment. For instance, clear amorphous polymers such as APET and PVC are suitable for use at room temperature and freezing, but are not microwaveable.



Key: HDPE = High Density Polyethylene
PP (ho) = Polypropylene homo-polymer
PP (co) = Polypropylene co-polymer
APET = Amorphous PET
CPET = Crystalline PET
GPS = General Polystyrene
OPS = Oriented Polystyrene
HIPS = High Impact Polystyrene
PVC = Polyvinyl Chloride
PET = Polyethylene Terephthalate

Figure 3.1: Temperature properties of commodity plastics for food packaging applications. [5]

3.2.3 Rigidity

Elastic modulus is a parameter reflecting the rigidity of materials i.e.: the ability of an object to resist elastic deformation when subjected to a force. The elastic modulus of a material is defined as the slope of its stress- strain curve, where λ (elastic modulus) = stress / strain. The elastic modulus is an important property for the rigidity of packaging products as the polymer must have a high enough elastic modulus to produce for example a thermoformed plastic tray rigid enough to protect its contents.

Figure 3.2 compares the 'E value' for a range of plastics for food packaging. It is worth noticing that rigidity of a packaging is not solely determined by the elastic modulus of the materials, which may vary depending on plasticization, but also by the gauge thickness of the sheet and the design of the packaging. For example PP has a comparatively low rigidity so may require increased gauge thickness relative to other materials. However this may be partially compensated for by its low density.

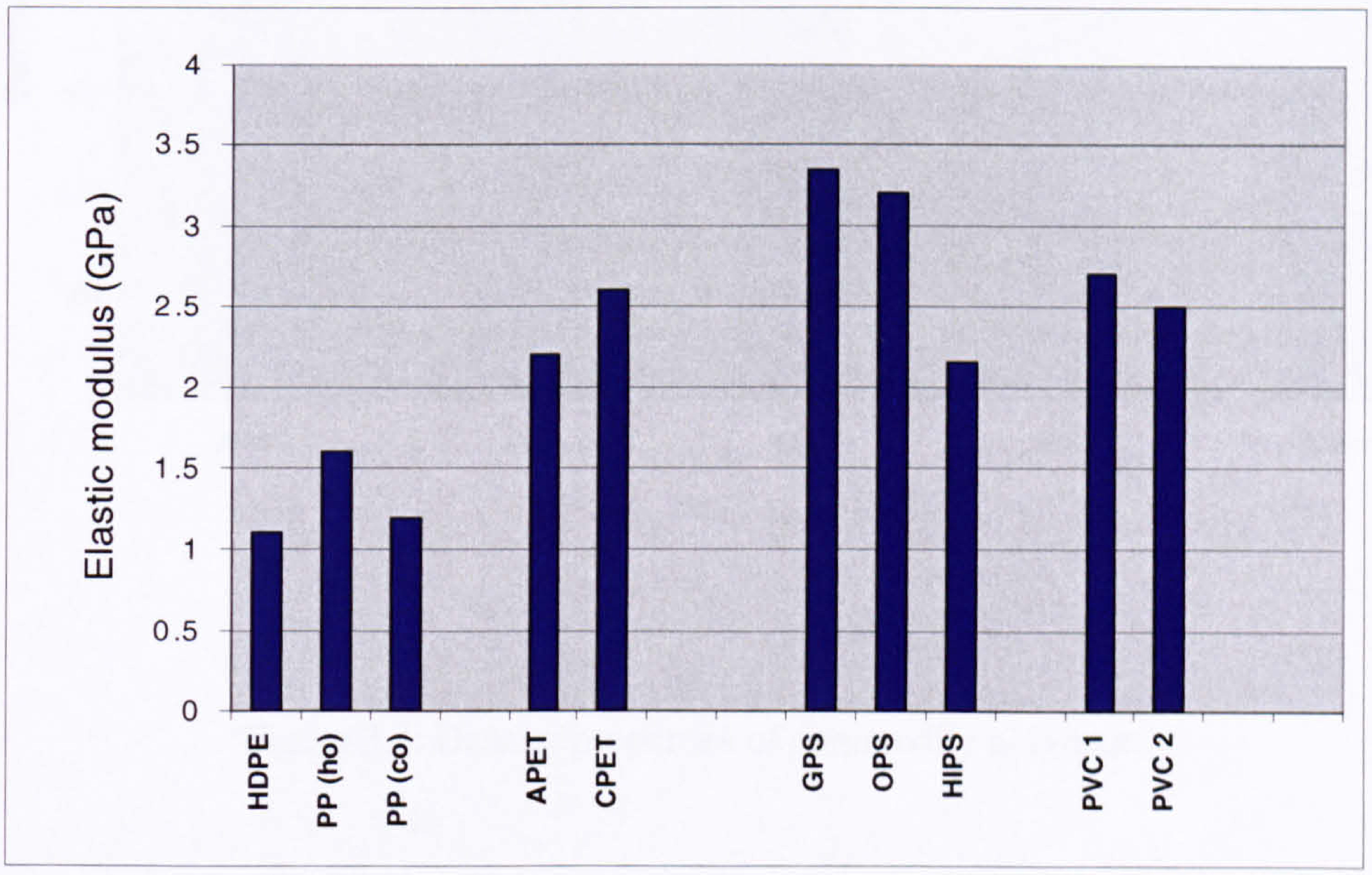


Figure 3.2: Elastic modulus of commodity polymers [5].

3.2.4 Density

The density of water is equal to 1000 kg/m^3. This is used as the benchmark when comparing different materials. PP has a density of 900 kg/m^3, which is lower than that of water. APET and PVC both have the highest density approximately 1375 kg/m^3. When compared with APET or PVC of the same gauge thickness, PP is approximately 33% less dense for an identically designed packaging container (Figure 3.3).

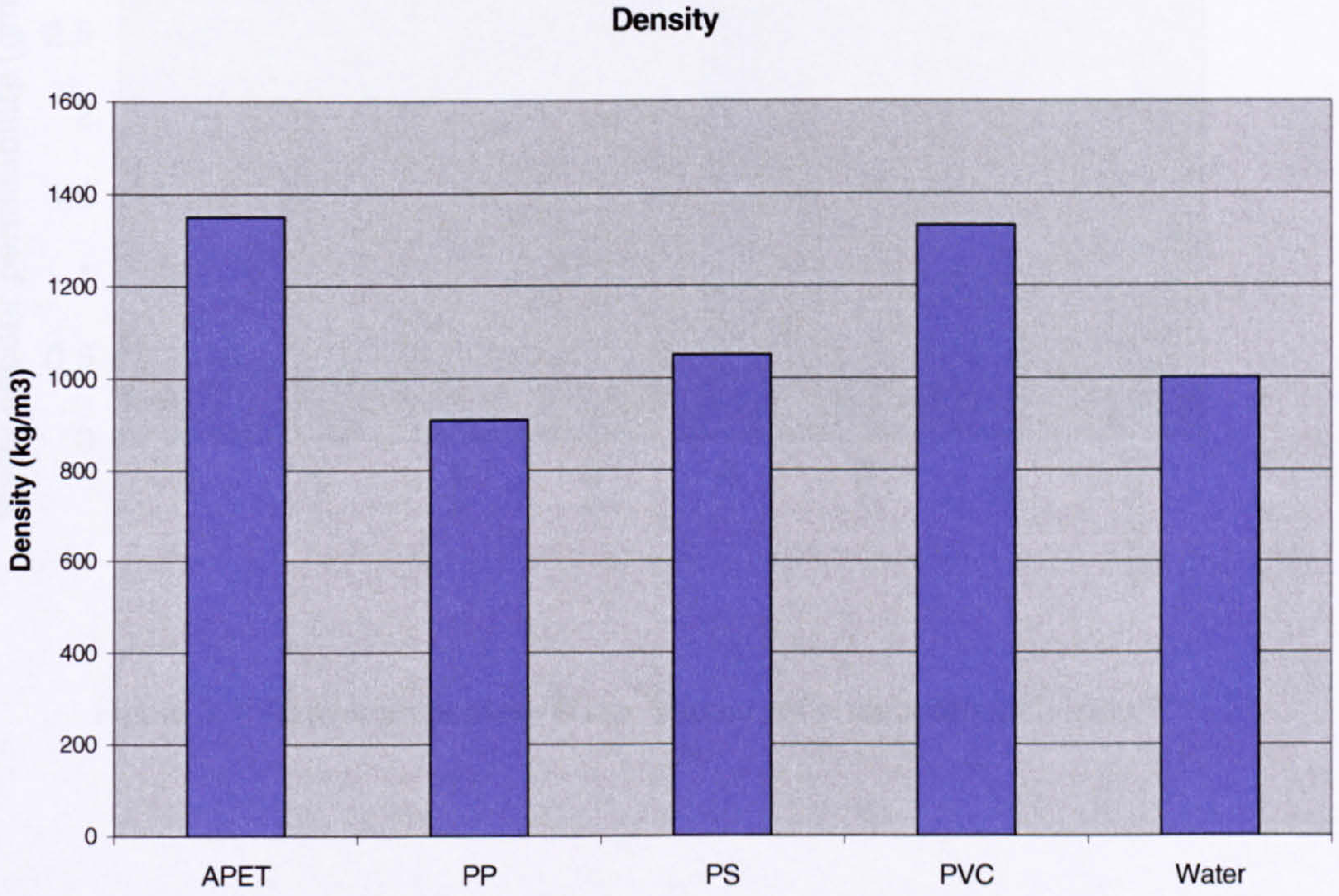


Figure 3.3: Density properties of commodity polymers

3.2.5 Barrier Properties

Plastic packaging helps food stay fresh for longer periods. A water vapour barrier helps maintain a desirable environment within packaging so as to prevent food products absorbing or loosing water. An oxygen barrier is very important as many foods decompose more quickly when in an oxygenated atmosphere.

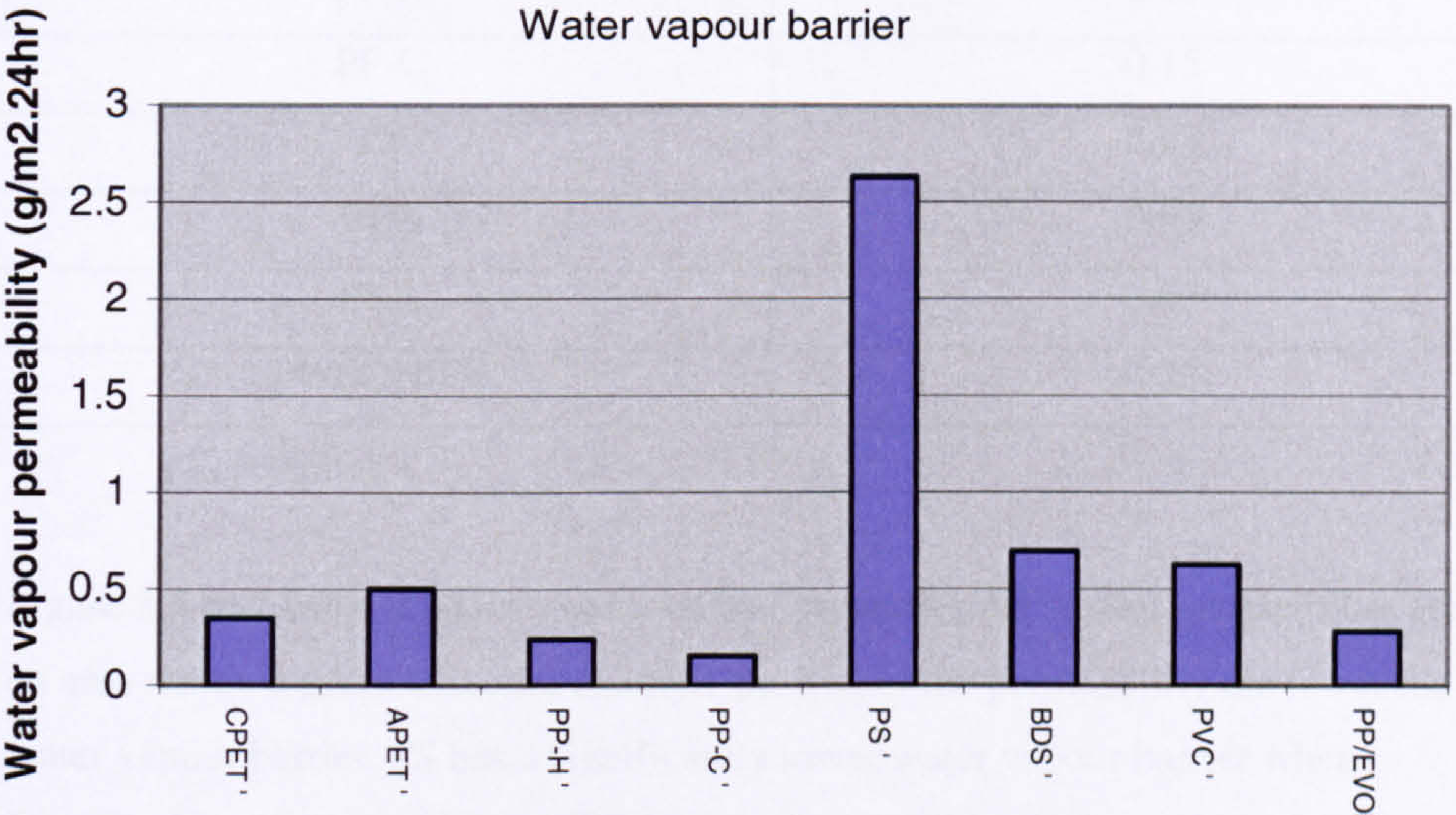


Figure 3.4: Barrier properties (Water Vapour) of commodity polymers [6]

Table 3.2: Barrier properties (Water Vapour) of commodity polymers [6]

Material Type	Water Vapour Barrier (g/m^2 over a 24 period)
CPET	0.35
APET	0.50
PP-H	0.23
PP-C	0.15
PS	2.63
BDS	0.69
PVC	0.63
PP/EOH/PE	0.28

Figure 3.4 and Table 3.2 show water barrier properties (as vapour permeability across an area within a given time) for example the higher the permeability the lower the water vapour barrier. PS has a significantly lower water vapour barrier when compared to all other polymers. PP (copolymer) exhibits the lowest water vapour permeability and therefore has the most affective barrier.

Figure 3.5 and Table 3.3 shows the oxygen permeability of a selection of plastics. Materials having low oxygen permeability are used for oxygen barriers. An oxygen barrier is very important as many foods decompose more quickly when in an oxygenated atmosphere. PVC, APET and CPET are very good oxygen barriers and are used when packaging extended shelf life products, for example, mixed gas flushed meat packs. PS and PP have low oxygen barrier properties.

Multi-layer film/sheet are often used to enhance barrier properties in plastic packaging. For example, when PP is combined with a thin layer of EVOH, approximately 5 – 20 micron thickness, oxygen barrier properties can exceed APET and PVC. Multi-layer film is often used to optimise both water vapour barrier and oxygen barrier properties a multi layer film is used, for example, PP / EVOH / PE. Where PP is used to provide a maximum water vapour barrier, EVOH is used to provide a maximum oxygen barrier and PE is used for high weld strength.

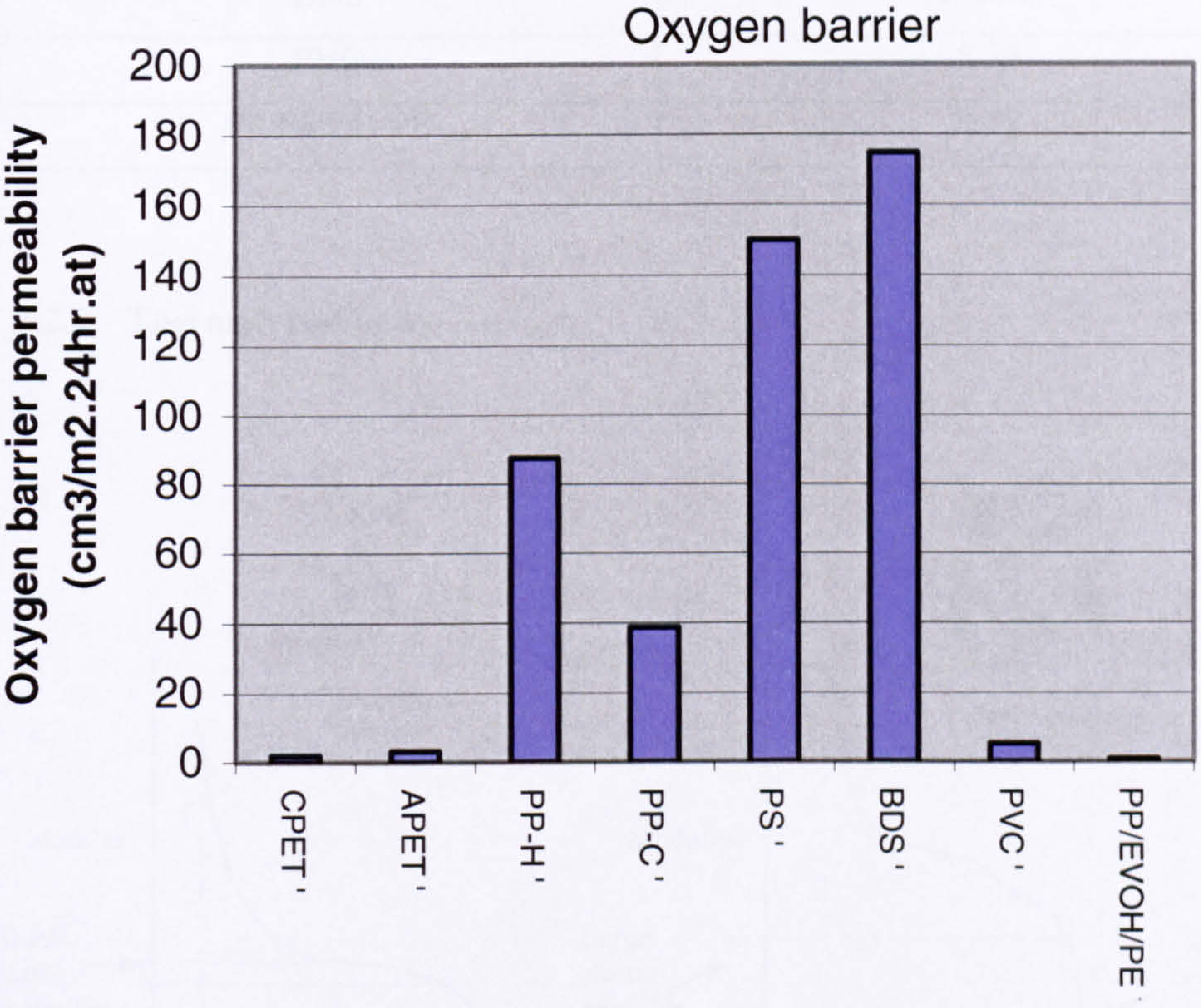


Figure 3.5: Barrier properties (Oxygen) of commodity polymers [6]

Table 3.3: Barrier properties (Oxygen) of commodity polymers [6]

Material Type	Oxygen barrier permeability (g/m2 over a 24 period)
CPET	1.8
APET	3.25
PP-H	87.50
PP-C	38.75
PS	150.00
BDS	175.00
PVC	5.25
PP/EVOH/PE	0.72

3.2.6 Thermoformability

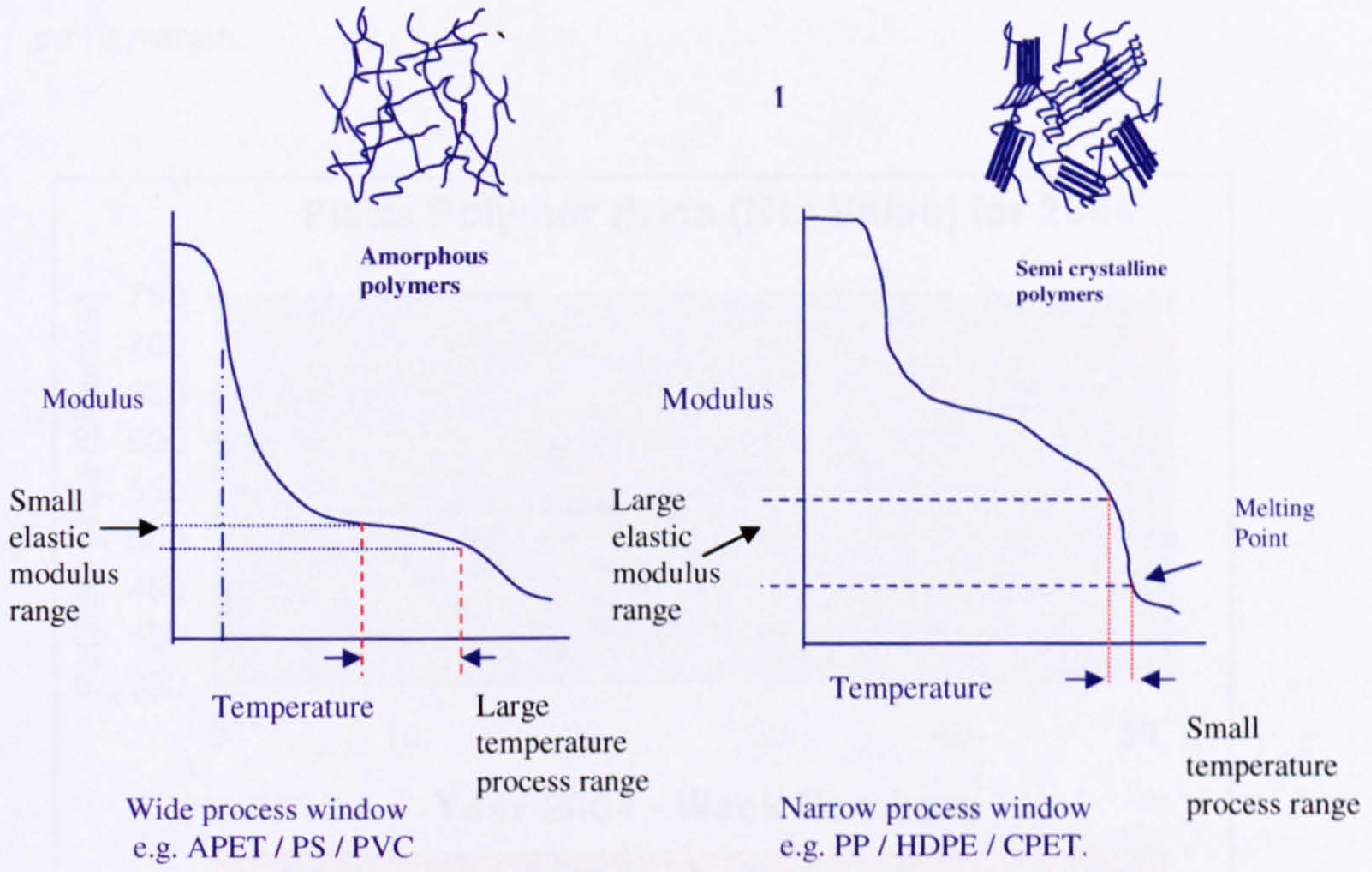


Figure 3.6: Thermoformability of relevant polymers. [7]

Thermoplastics are formed into a desired shape in a suitable temperature range where the materials are sufficiently soft (low shear or elongation modulus) without thermal decomposition. Polymers with an amorphous structure, such as APET, PVC and PS (as shown Figure 3.6 of the left graph), have a relatively large temperature range for processing between their softening and decomposition points of, approximately ± 20°C.

By contrast, semi- crystalline materials such as PP have a softening point very close to the melting point of the polymer. This results in a narrow temperature process range of approximately ± 5°C, thus making the forming process more difficult to control.

3.2.7 Prices of Commodity Polymers

Supply and demand largely dictates the relative prices of commodity polymers prices are often tracked by polymer processing companies as large variations in prices can occur over short periods (Figures 3.7 and 3.8), which in turn can affect the overall profit margin.

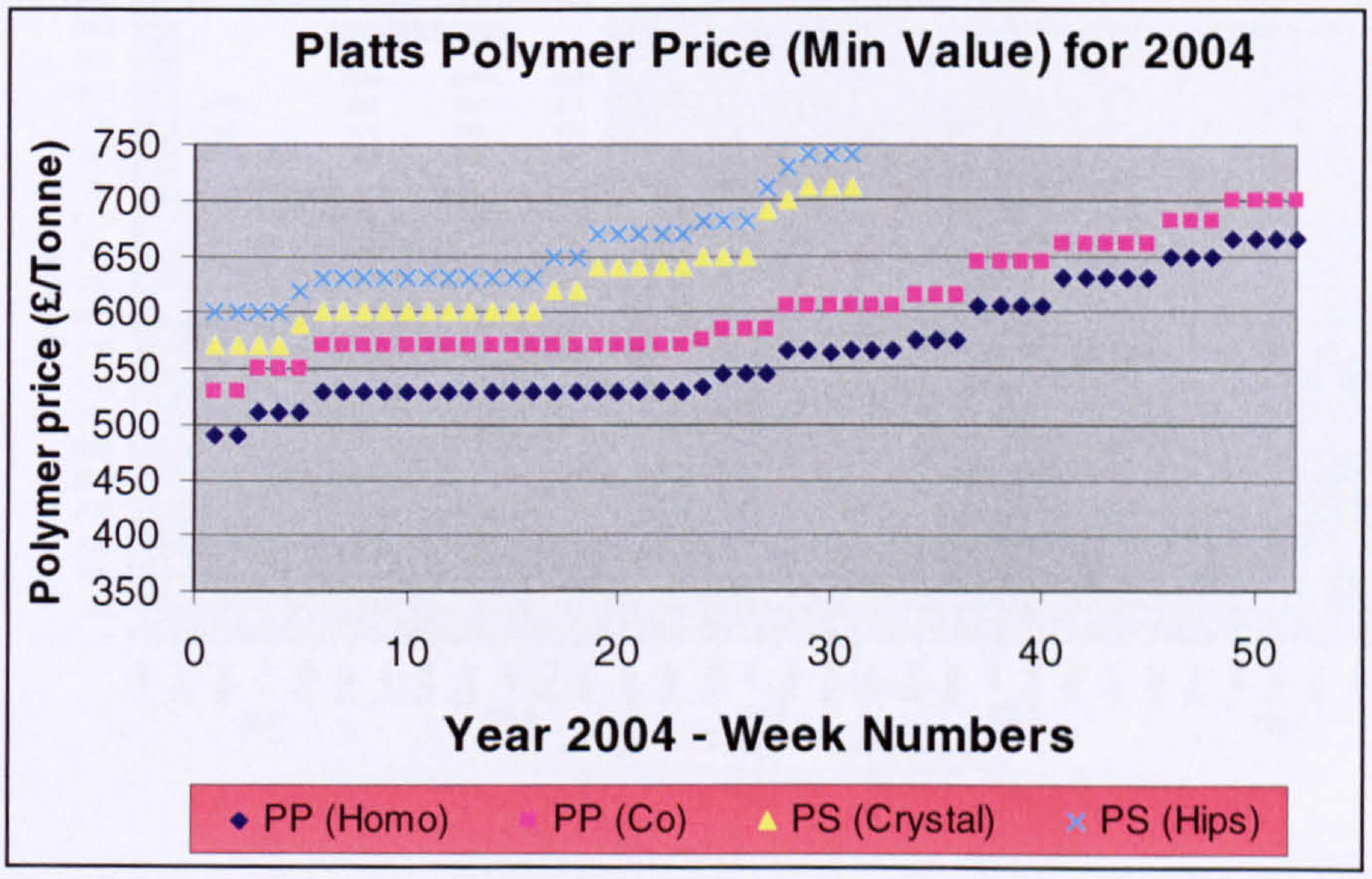


Figure 3.7: Price of traditional commodity polymers for the 2004 period [8].

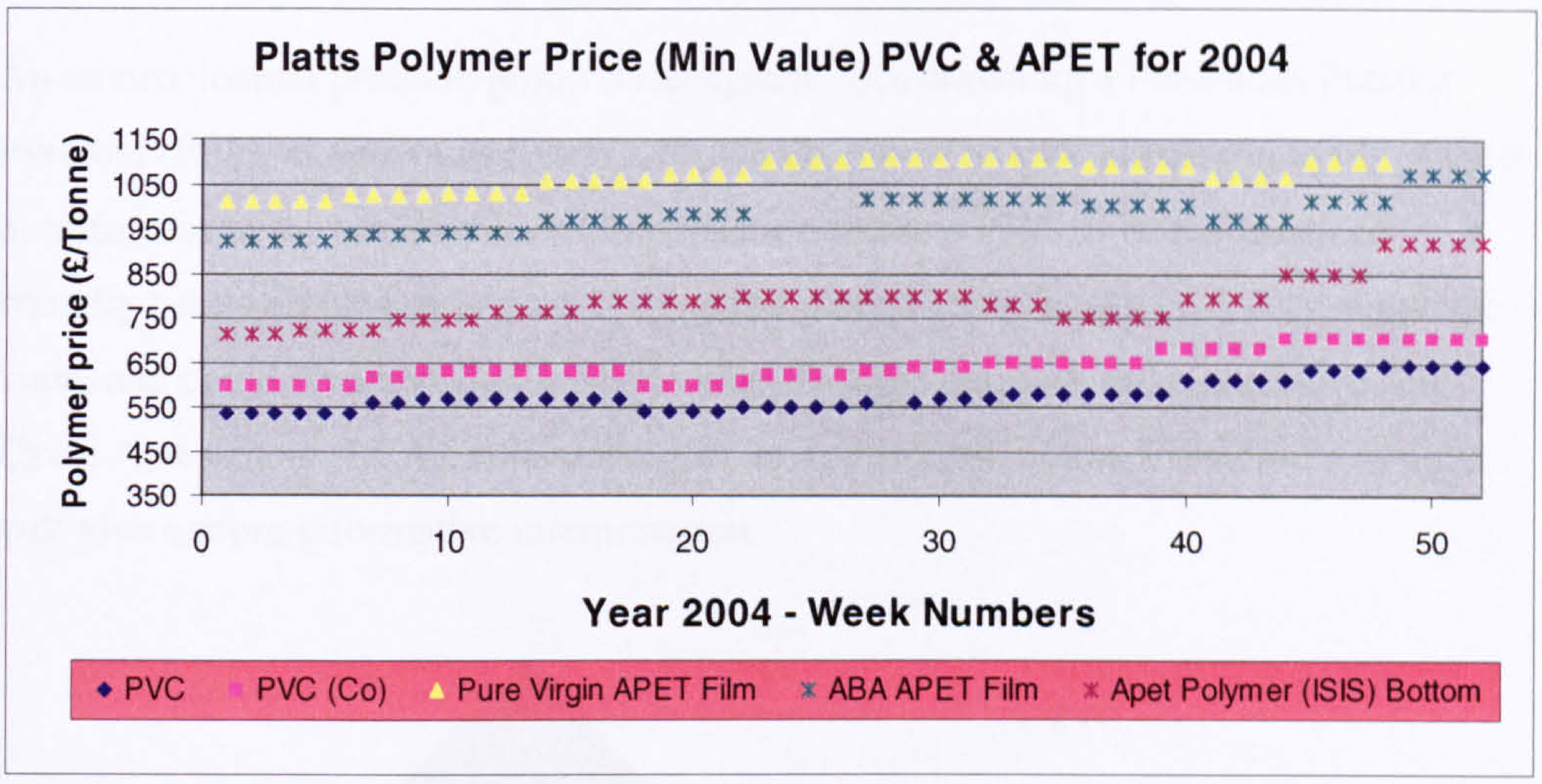


Figure 3.8: Comparison between PVC and APET polymer prices for the 2001 period [8].

When looking at the longer-term price change, it is much more turbulent (Figure 3.9), which can be attributed to the change in the price of a barrel of oil.

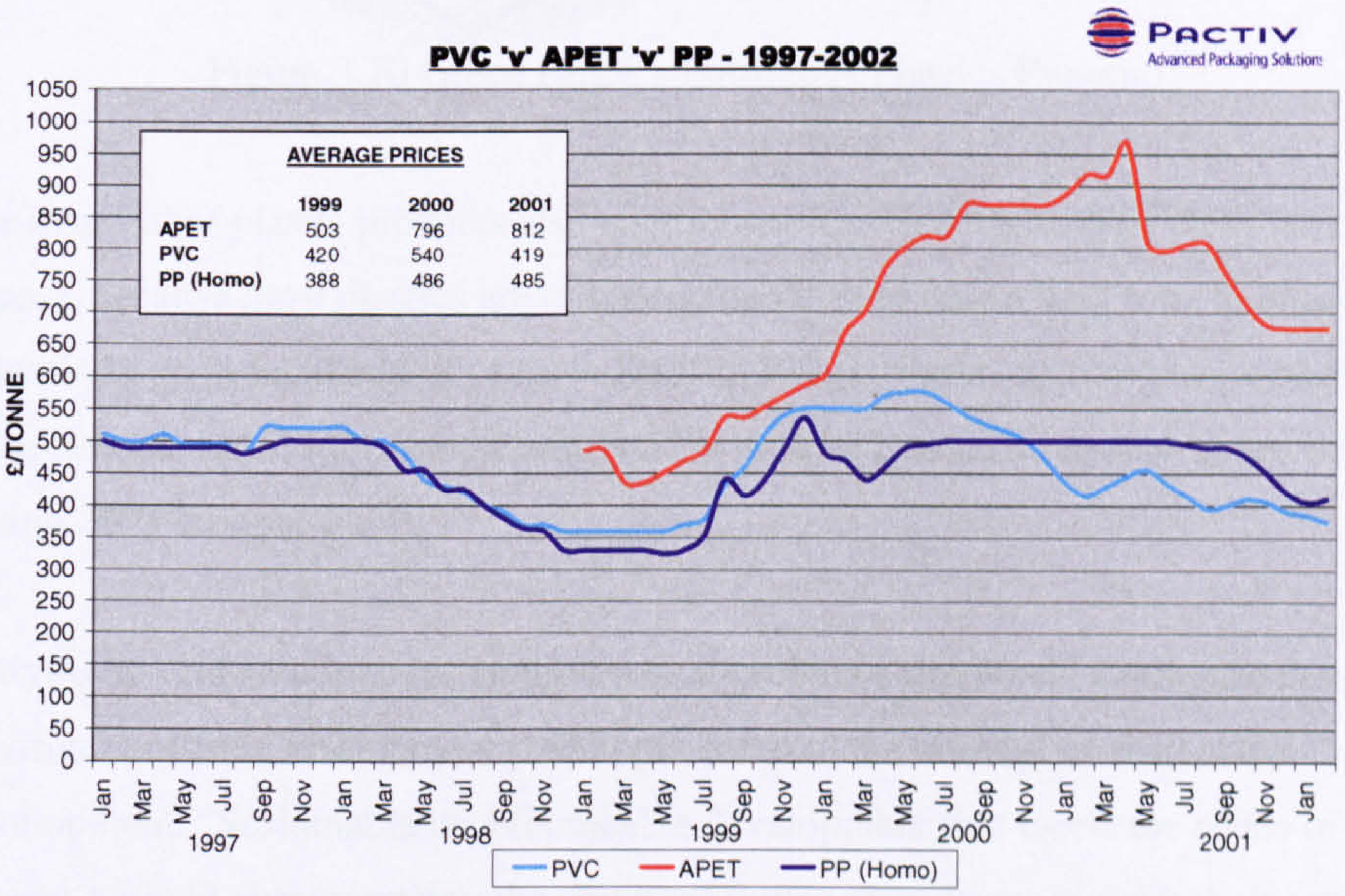


Figure 3.9: Commodity prices of traditional polymers for the 1997 – 2001 period [8].

3.2.8 Environmental Perception of Plastics

An environmental pressure group 'Greenpeace' has drawn up a Poisonous Plastics Pyramid (PPP), as shown in figure 3.10, which claims to rank plastics in terms of their harmfulness to the environment. Greenpeace considers PVC to be the least eco-friendly because chlorine is used in its production. This is, however, a very simplistic view, and could be deemed to be misleading in some cases. A more extensive Life Cycle Assessment (LCA), considering all environmental factors from cradle to grave, will give a more informative interpretation.

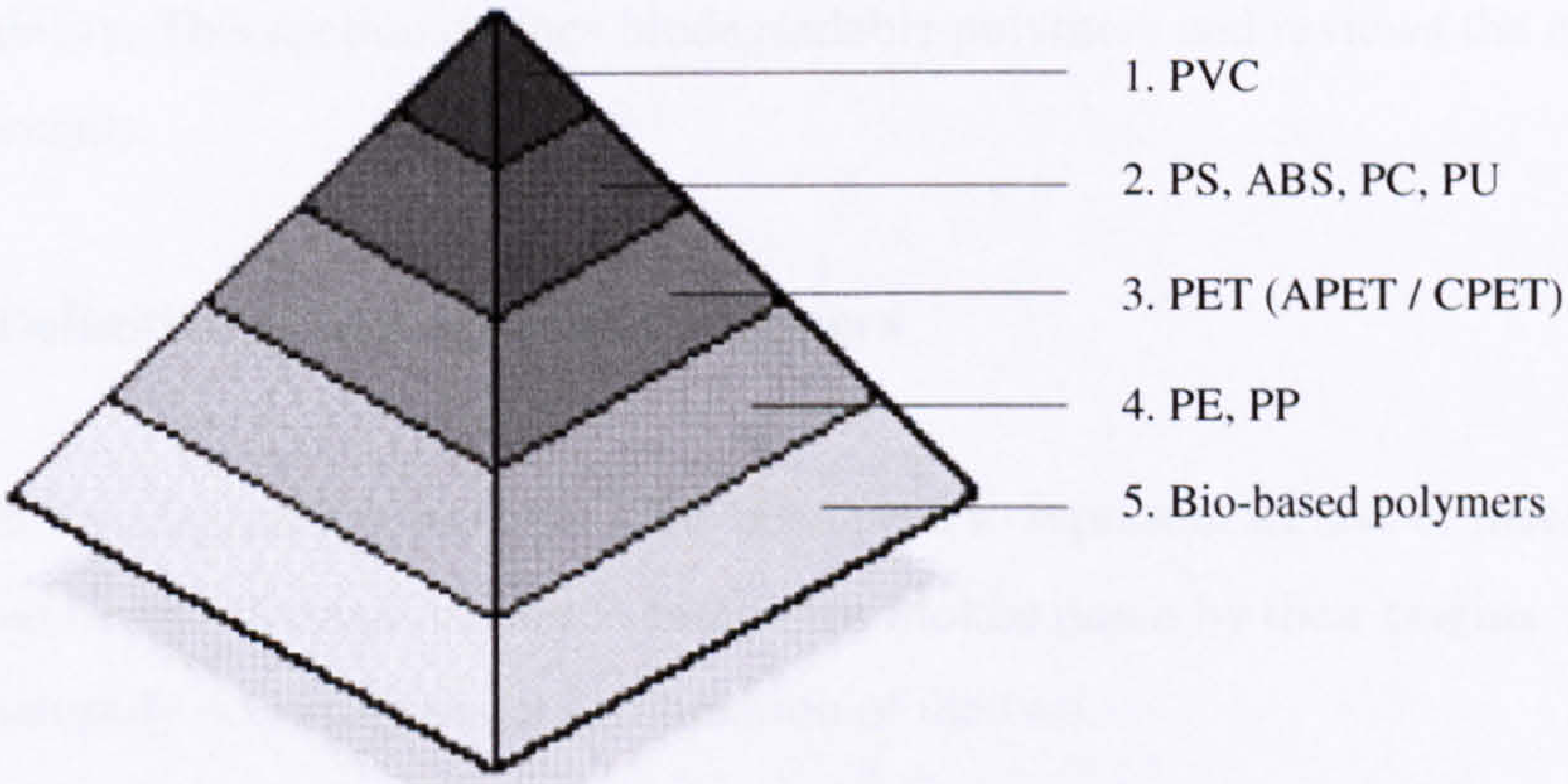


Figure 3.10 Green Peace's Poisonous Plastics Pyramid [9]

The disposal of plastic products also contributes significantly to their environmental impact, because most plastics are non-degradable, they take a long time to breakdown, potentially up to hundreds of years in landfill. Plastic waste, such as plastic bags, often become litter, for example nearly 57% of litter found on beaches in the UK during 2003 was plastic [9].

In trying to find solutions for environmental problems the World Commission on Environment and Development (1987) put forward the concept of sustainable development. "Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs[10]."

There are some problems with this concept. Namely, we are very aware of the environmental problems of today but we don't fully understand what lies ahead. Some future problems are easier to predict due to them having roots in existing problems. There are problems, however that do not or are not known to currently exist. This is the challenge that we as a human race have set ourselves.

3.3 Biodegradable polymers for packaging

During the last decade, polymers obtained from renewable resources have attracted increasing attention, due mainly to their environmental image and potential for sustainability. This section defines biodegradable polymers and reviews the major developments.

3.3.1 Definition of Biodegradable Polymers

The term "b*iodegradable polymer*" has been used to represent a class of materials. These can be sub-divided into three categories broken down by their origins: i.e. oil-based, naturally occurring and a combination of the two.

1. Biodegradable plastics, such as Polycapolactone, polyhydroxybutyrate and polyvinyl alcohol are synthetic polymers derived from a traditional petrochemical process, but exhibit degrees of biodegradability [11].

2. Biopolymers are naturally occurring long chain molecules (cellulose, polysaccharides, proteins and DNA) or materials made from or derived from these natural polymers (PLA). Unlike synthetic polymers most of them are biodegradable.

3. Biopolymer complexes are made from a combination of biodegradable plastics and biopolymers and offer advantages such as lower costs and enhanced functionality (biodegradation). Examples include Materbi [12], which is made up of complex materials consisting of starch and synthetic biodegradable plastics.

3.3.2 Developments of Biodegradable Plastics

Biodegradable plastics are based on petroleum resources obtained chemically from synthetic monomers [13][14][15][16][17][18][19]. They are distinguishable by their oil-based origin. Their high prices mean that they are not widely used in the packaging industry.

3.3.2.1 Aliphatic Copolyesters

A large number of oil-based aliphatic copolyesters are biodegradable. They are manufactured from a combination of diols (such as 1,2-ethanediol, 1,3-propanediol, or 1-4-butadenediol) and dicarboxylic acid (adipic, sebacic or succinic acid).

- Showa Highpolymer from Japan has developed a range of polybutylene succinate/ adipate (PBSA), using adipic acid, sold under the name Bionolle® [19]
- Ire Chemical from Korea has developed a similar range of PBSA sold under the name EnPol®
- SK Chemicals from Korea has developed a material from the polycondensation of 1,2-ethanediol, 1,4-butadenediol with succinic and adipic acids sold under the name Skygreen®
- Nippon Shokubai from Japan sells an aliphatic copolyester under the name Lunare SE® [20]

The degree of biodegradability of these products depends on their structure. The addition of adipic acid, decreases the crystallinity of the material [21] and increases its ability to biodegrade [22]. Ratto et al states that the addition of a starch filler significantly improves the rate of degradation [23].

3.3.2.2 Aromatic Copolyesters

Aromatic copolymers are based on terephthalic diacid, which modifies material properties such as melting temperature and according to Muller et al [22] decreases the degradation rate. Examples include:

- Eastar Bio® manufactured by Eastman Chemicals in the USA
- Ecoflex® manufactured by BASF in Germany
- Biomax® manufactured by DuPont in the USA

3.3.2.3 Polycaproletone

Polycaprolactone (PCL) has been manufactured by ring-opening polymerisation in the presence of aluminium isopropoxide [13][14][24]. PCL is used in application such as controlled release of drugs and soft compostable packaging, utilising its biodegradable characteristics. PCL has a very low T_g (-61°C) and a low melting point (65°C) and is therefore generally either blended [25][26][27][28] or modified by copolymerisation or crosslinked [29]. Examples include:

- CAPA® manufactured by Solvay in Belgium
- Tone® manufactured by Union Carbide in the USA
- Celgreen® manufactured by Daicel in Japan

Tokiwa and Suzuki [30] discussed the hydrolysis of PCL and fungi degradation, proving that PCL can be enzymatically degraded. Bastioli [27] proved that PCL is biodegradable, but the rate of homopolymer hydrolysis is low. The addition of starch can significantly increase PCL rate of biodegradation [27].

3.3.3 Developments of Biopolymers

Biopolymers are polymers synthesised in nature or derived from natural and renewable materials. There are four methods of obtaining useful polymers from biological systems:

1. Direct production of a useful biopolymer as a natural part of the functioning of the biological system
2. Modifying the metabolism of a living system to generate a useful biopolymer
3. Making monomers from bio-feed stocks that can be conventionally polymerised
4. Breaking down biomass into synthesis gas – a mixture of CO and H_2 that chemical plants can convert into building blocks for polymers. [3]

Research is currently being carried out into the commercial applicability of biotechnology to the development of new products involving the use and modification of natural substances such as starch, cellulose, silk and others. Currently, few plastics are derived from natural products such as wood, starch and natural oils. Renewable raw materials are of industrial interest if their structure leads directly to polymers or to intermediates and monomers that are easy to produce and convert. However, as a source of chemical base products, they have several disadvantages with respect to petroleum. Generally renewable raw materials are chemical compounds or mixtures of chemical compounds and hence quite complex in composition and in terms of their properties. Their carbon: hydrogen ratio is less favourable for the manufacture of base chemicals and their conversion into intermediates or monomers also requires more energy than with petroleum [3].

The two major types of commercialised biopolymers are:

- Starch biopolymers – ie: those that use starch as a polymeric material
- PLA – a biopolymer derived from starch

3.3.4 Starch Biopolymers

The incorporation of starch into commodity plastics, with a view to the starch enhancing the biodegradability of the material, has generated worldwide interest. This is for a variety of reasons including cost (starch is the cheapest biopolymer) and the fact that starch breaks down into carbon dioxide and water.

Starch based biopolymers have been the main focus of this research and therefore have been described in more detail.

3.3.4.1 Starch

Starch is an inexpensive, naturally abundant renewable product extractable from a large range of plants. Together with cellulose, starch can be extracted industrially from major food crops such as wheat, rice, maize, potato, as well as tapicoa, sweet potatoes, oat, barley, peas, beans, sorghum, arrowroots and sago.

Starch is biodegradable and can be broken down and assimilated by natural means back into elements such as carbon, oxygen and hydrogen in a wide variety of environments. The degradation or incineration of starch products recycles the atmospheric CO_2 trapped by starch producing plants during their growth, thus closing the biological carbon cycle. These properties allow the development of totally degradable products for specific markets needs.

Starch is the assimilation product made in the green plant cells and in several microorganisms. Similar to other naturally occurring carbohydrates, such as glycogen and cellulose, starch is a polysaccharide consisting of only a glucosidic unit, which is referred to as a homoglucan [31].

Starch is constituted by two major components:

1. Amylose is a linear or sparsely branched polymer of a molecular mass in the range of 10^5 to 10^6 g/mol linked primarily by 1-4 bonds (Figure 3.11). Amylose chains very easily form a spiral-shaped single or double helix.

2. Amylopectin (Figure 3.12), an alpha D (1-4) glucan, which has alpha D (1-6) linkages at the branch point. The other main component of starch 'amylopectin' is highly multiple branched with a molecular mass of 10^7 to 10^9 g/mol. Like amylose, amylopectin contains 1 to 4 linked glucose units, but has an additional 1 to 6 glucoside branching points occurring every 25 – 30 glucose units [31][32][33].

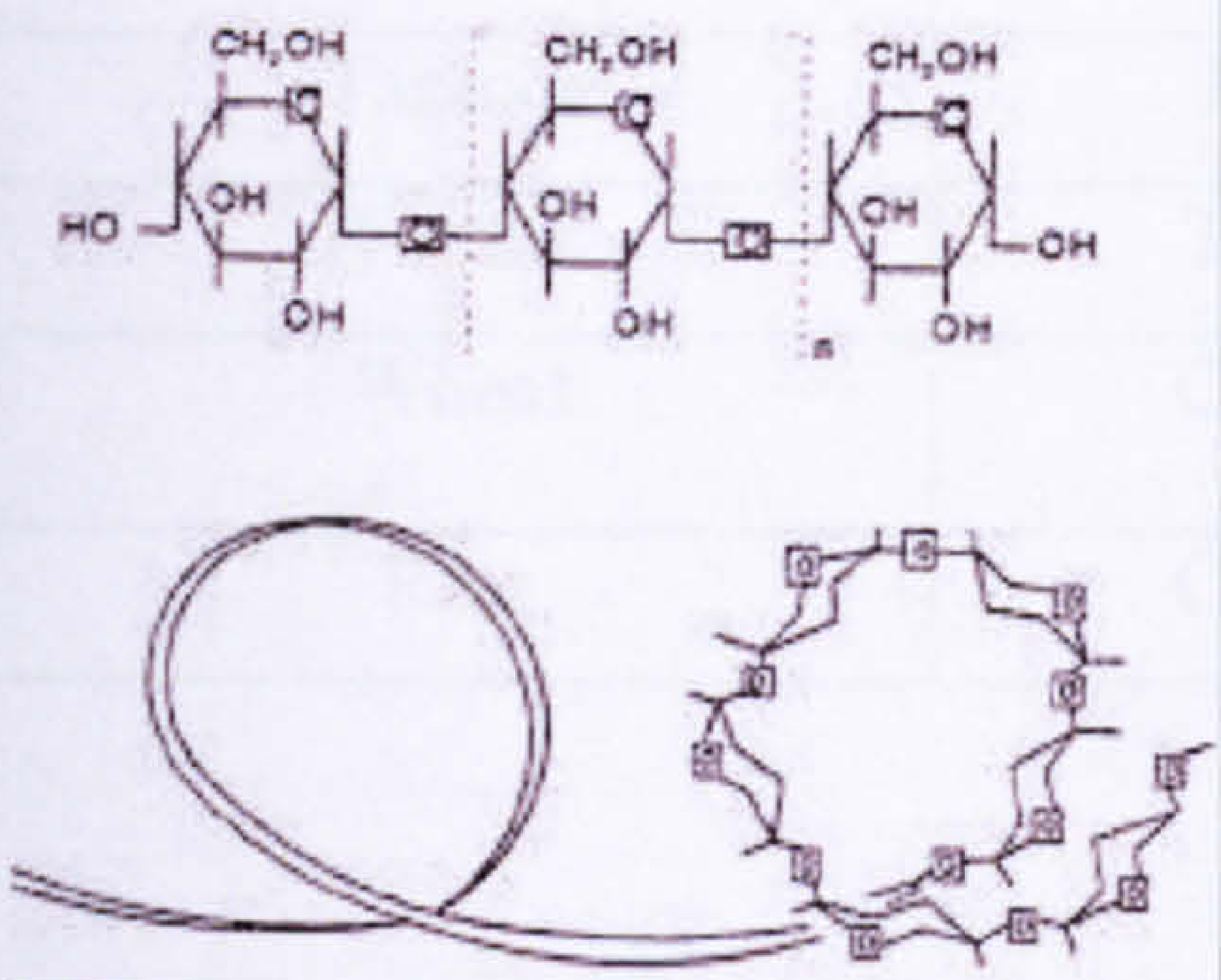


Figure 3.11 Amylose

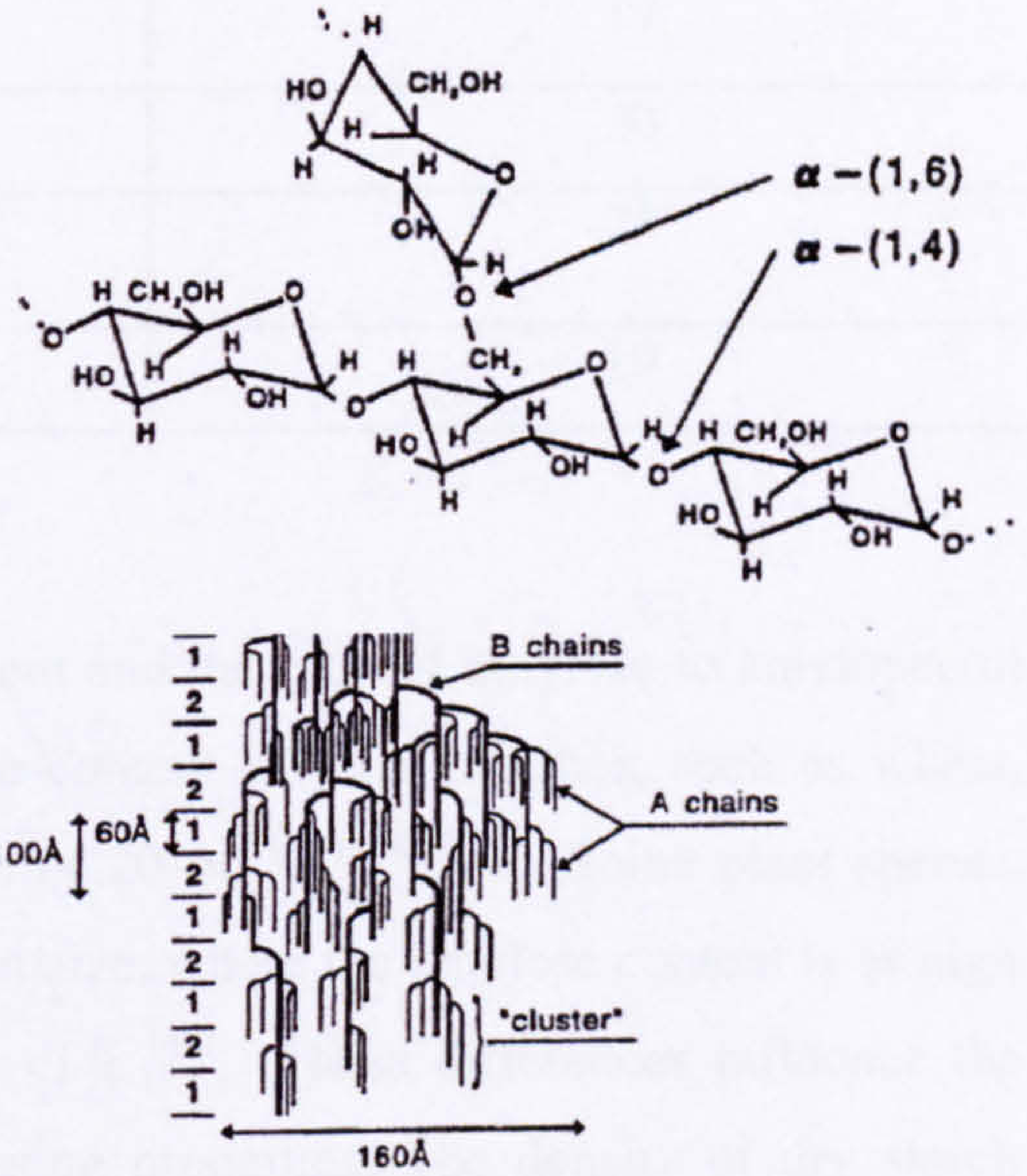


Figure 3.12 Amylopectin

Starch molecules have dimensions from 0.5 to 175µm in a variety of shapes [31]. The linear amylose molecules of starch have a molecular weight of 0.2 – 2 million, while the branched amlopectin molecules have molecular weights 100 – 400 million [34][35].

Hizukuri [36] proposed a cluster model composed of short chains (with a number average degree of polymerisation (DP), where $DP_n \approx 17$) in clusters attached to longer chains (where $DP_n \approx 60$) where 80-90% of short chains in the clusters interconnect[36]. (Figure 3.12) Maize and amylomaize have several intermediately branched structures which resemble that of amylopectin.

Table 3.4 Starch sources and their amylose content.

Starch Source	Type	Amylose Content (%)
Regular maize	Cereal	25
Waxy maize	Cereal	<1
High amylose maize	Cereal	50 – 70 – 90
Tapioca	Root	17
Potato	Tuber	20
Wheat	Cereal	25
Rice	Cereal	19

Types of starches can differ in water content and the ratio of amylose to amylopectin [37][38]. Table 3.4 shows that the amylose content of most starches, such as wheat, regular maize and potato are in the range of 20–30 % [37][38][39]. Some plant species have altered starch content, such as amylomaize, where the amylose content is as high as 50–90% and waxy starches as low as <1% [40]. These differences influence the physical properties as well as the processing properties. The density of dry starch varies from 1.514 to 1.52 g/cm^3 whereas the density at equilibrium moisture content varies from 1.468 to 1.485 g/cm^3.

3.3.4.2 Starch Incorporated into Plastics

The incorporation of starch into commodity plastics resulted in the first generation of 'biodegradable plastics', with a view to the starch enhancing the biodegradability of the material, has generated worldwide interest. This is for a variety of reasons including cost (starch is the cheapest biopolymer) and the fact that starch breaks down into carbon dioxide and water. Granular starch has been used as a filler in plastics since the late seventies [40]. PE/Starch films have since been developed using whole granules of starch, which has limited the addition of starch to 10 wt% or less.

The late seventies also saw a second-generation starch/ plastic combination. Investigations concluded that the starch granule structure is totally disrupted in the starch/ plastic combination [41][42][43][44][45]. The starch formed a continuous phase rather than simply being present as a particulate filler. The addition of up to 50% starch was possible, whilst still maintaining acceptable properties. Several products have been marketed based on the second generation starch plastics [46][47]. Others have tried graft polymerisation of starch onto several hydrophilic polymers [48]. Treatment of starch with ceric ammonium nitrate in water yields free radical sites on the starch backbone that can act as macro-initiators in the presence of various monomers to give polymer grafts of high molecular mass. Extensive research has been carried out on polymers of this type, in particular starch-g-poly (methyl methacrylate) [48].Graft co-polymers have been prepared from granular as well as plasticized starch. Extruded plastics with good mechanical properties are obtained from starch-g-poly (methyl methacrylate) containing 40 –60% starch.

3.3.4.3 Destructurised Thermoplastic Starch

The development of plastic which contain starch raised the question: "What is a truly biodegradable plastic?" This in turn has lead to the development of 'truly biodegradable plastics.' The ultimate goal of the research is to prepare consumer items for one-time use from substantially pure starch and to exclude non-biodegradable synthetic polymers from the formulation.

The materials still use vegetable starch, but not as a filler or grafted filler. Instead granular starch is mixed with enough plasticizer to enable melt below the decomposition temperature of starch (T_d) yielding a product where the starch polysaccharides form either a continuous polymeric entangled phase or a completely disordered molecular structure of the granular starch. This is referred to as thermoplastic starch, or destructurized starch [49][50]. These are lauded as new materials with comparable properties to well known hydrophobic thermoplastics.

Various solutions from agriculture have been investigated, with starch being the most favoured option due to its low cost and biodegradability. The biodegradability and material properties of starch make it a promising raw material for the compounding of a thermoplastic polymer from a renewable source. Under the action of high temperature and shear, starch can be processed into a mouldable thermoplastic [51][52][53].

Destructurised starch is essentially amorphous starch made from granular starch of which the granular supermolecular structure and crystallinity is completely transformed into a homogenous polymer matrix by thermochemical processing irrespective of the type of additives or storage conditions after processing. Destructurised starch is referred to as thermoplastic starch when it can be processed by thermoplastic processes such as extrusion, thermoforming, injection moulding, blow moulding and compression moulding into shaped forms without the addition of extra plasticizers or melt flow accelerators. This can be achieved by blending different modified starches and other biopolymers, either biodegradable or derived from natural renewable materials, to obtain final products. Destructurised starch may also be modified to enable specific functionalities.

3.3.4.4 Products made from Starch Biopolymers

Examples of products made from Starch Biopolymers include:

1. Starch food trays using baking technology: One of the examples of successful starch biopolymer products for food packaging is food trays manufactured using waffle-baking technology.

   Waffle baking technology is well known in food industry for the production of ice cream cones and biscuits. In this process an aqueous suspension of wheat is deposited on a heated mould. Under heat, a gelatinisation of flour occurs and water starts to turn into vapour, which creates a dry foam with a cellular structure.

   This technology has been further developed and applied to fabricated food trays and one of the food manufactures of such food containers is Potatopak Ltd.

Potatopak Ltd is a UK company, incorporated in 2000, which has acquired the intellectual property rights and patents. Manufacturing packaging products, which are 100 % biodegradable and 100 % compostable. The products are also non-toxic and are not harmful to human, animal or marine life, even if eaten by mistake! [54]

The products are manufactured from four principal ingredients. The main one being potato starch. The ingredients are compression moulded to produce a form of packaging with many potential uses, particularly in the food packaging industry. Potatopak intend to enter into the fast-food catering industry, which is becoming increasingly conscious of the environmental impact of the business. Potatopak's products are regarded as ideally suited as disposable, serving plates, trays, bowls and burger boxes in what is potentially a very important market.

It takes 8 tonnes of potatoes to produce 1 tonne of starch, which in turn makes approximately 43,500 trays. Currently only imported starch has been used, however in the future it is hoped to utilise UK crop waste. It is estimated that that 20% of the UK potato crop waste is equivalent to 1.2 million tonnes, which can be produced into 6.5 billion trays [54].

2. Starch Based Multilayer materials: Champagne-Ardennes, one of the main French producers of cereals, formed a partnership with the University of Reims to produce multilayer materials consisting of starch and polymer films [55].

   Water and wheat starch formulations without other additives, resulted in trays with different weaknesses. The production is significantly longer, resulting in a high density. The trays have a tendency to crack when removed from the mould and warp a few hours after production. Improvements were made using a glycerine plasticizer, magnesium stearate release agent. Cellulose fibres were also added to produce materials with sufficient stiffness for use in packaging applications as shown in Table 3.5.

Table 3.5 Properties of combinations of starch and fibres.

Type of material	Young's Modulus (MPa)	Max Strength (MPa)	Strain at break (%)
1. core: starch + fibres skin: PCL	730	14.5	4
2. core: starch + fibres skin: Eastar Bio®	630	11.2	3

*Formulations: 1 and 2 can both be thermoformed at 78 and 90°C respectively.

The high water sensitivity and the changes in mechanical properties are the weaknesses which limit its use. Two kinds of multilayer materials were therefore manufactured with a core based on plasticized wheat starch core and a skin based on polycapolactone (PCL) or Eastar Bio®.

Films with a thickness of 500 – 700 micron and 350 mm wide were extruded. The film was thermoformed using continuous pilot machinery in negative mode, with blown air. The machine has a heating zone with a cooled mould, produced by Autobar. This produced good forming with both types of materials. Processing temperatures were lower than those used with conventional polymers, such as PVC, PP, PET, ie: less than 90°C. Cycles times where similar to conventional polymers mentioned.

Further testing included places the trays in a cold room, set to 4°C, and at ambient temperatures with a view to showing signs of ageing. Room temperature storage produced signs no significant effects with the exception of an increase in brittleness thought to be due to post processing ageing of the starchy core.

The biodegradations of the materials in Table 3.5 have been investigated in a compost. Rectangular samples were placed into nets and the weight was measured over a set time period. Figure 3.13, which shows the loss of mass versus time for a starch film, a co-extruded starch/PCL film and a co-extruded starch/EB film.

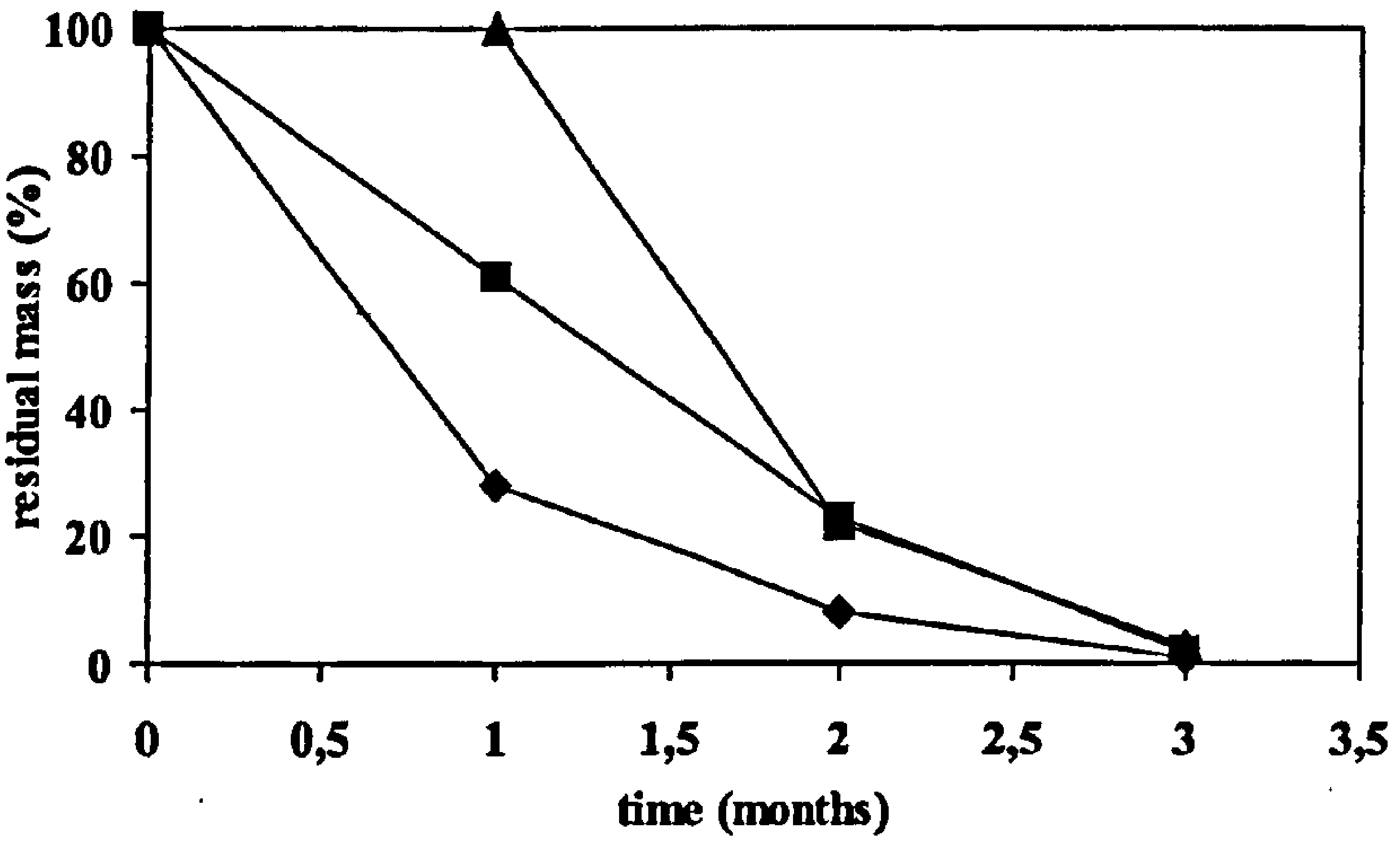


Figure 3.13: Evolution of mass versus time for starch film (♦), co-extruded starch/PCL film (■) and co-extruded starch/EB film (▲).

Further industrial trialing have resulted in the development of expanded and multilayer materials, which have improved behaviour in relatively high humid conditions. This is of particular interest for storage of fresh products and wet products, such as meat and fish, to replace conventional polymers, such as PVC, PS or PET.

3.3.4.5 Polylactic Acid (PLA) – A Biopolymer from the Bio-refinery of Starch

There are several trade names for PLA including:

- Natureworks manufactured by Cargill-Dow in the USA
- Lacty manufactured by Shimadzu in Japan
- Lacea manufactured by Mitsui Chemicals in Japan
- Heplon manufactured by Chronopol in the USA
- CPLA manufactured by Dainippon Ink Chem. In Japan
- PLA manufactured by Galactic in Belgium.

For this project Natureworks from Cargill-Dow was used as it was found to be the most suitable for thermoforming.

3.3.4.6 'Natureworks' from Cargill Dow

Polylactic Acid (PLA) is made from the polymerisation of lactic acid which is produced from starch by fermenting sugar. PLA is manufactured by Cargill Dow and is marketed under the trade name 'Nature Works.' Cargill Dow manufactures PLA on an industrial sized production plant in Nabraska, USA. The plant has a 140,000 tonne per year capacity and was commissioned in 2002[56].

Figure 3.14 shows a manufacturing overview of PLA.

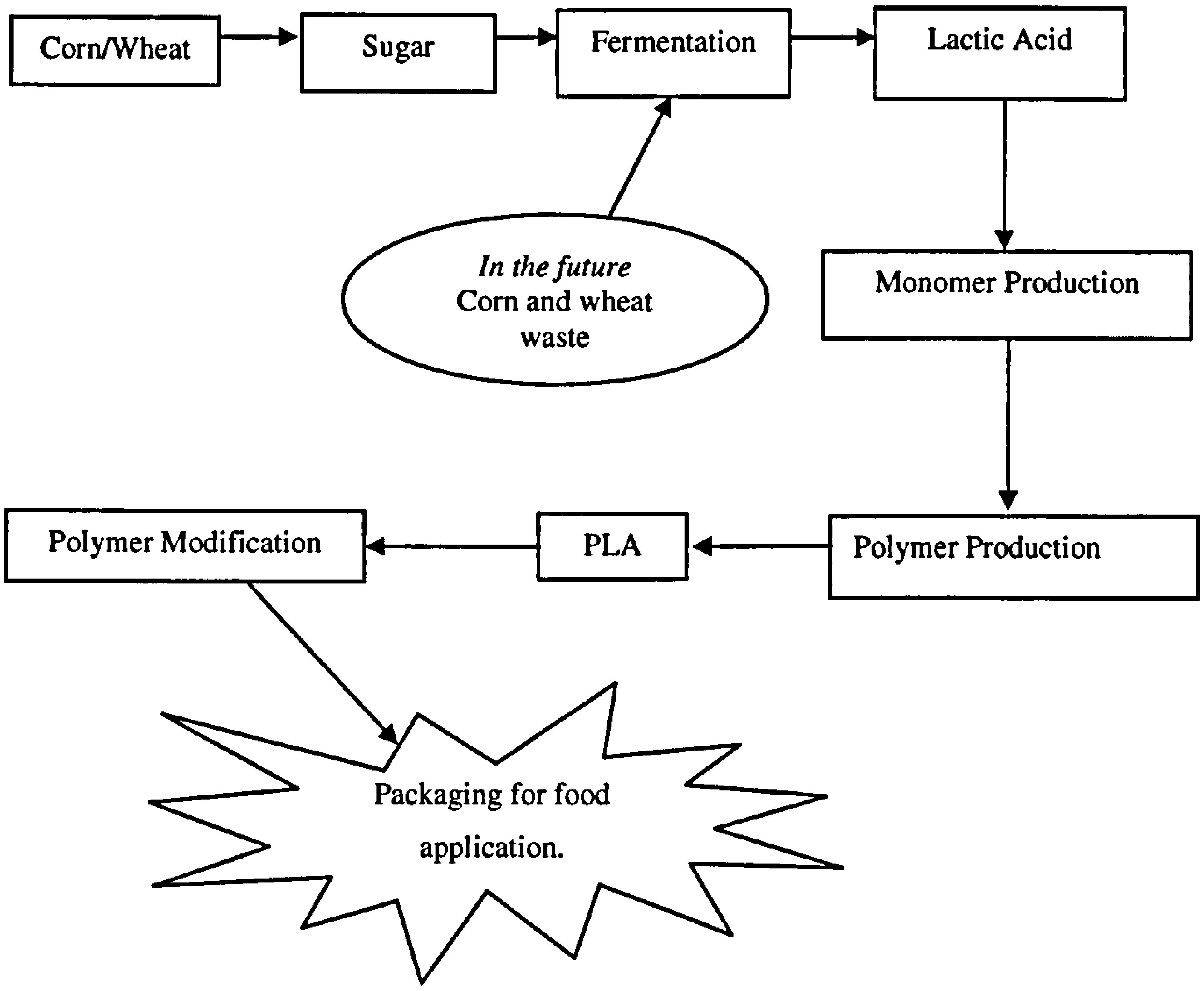


Figure 3.14: A manufacturing overview of PLA production

Figure 3.15 shows the chemical changes during the bio-refinery process. Currently corn and wheat are grown specifically for the use of manufacturing PLA. However, it is expected that in future, waste from these crops will be used. Figure 3.14 shows how this will fit into the manufacture of PLA making it truly sustainable.

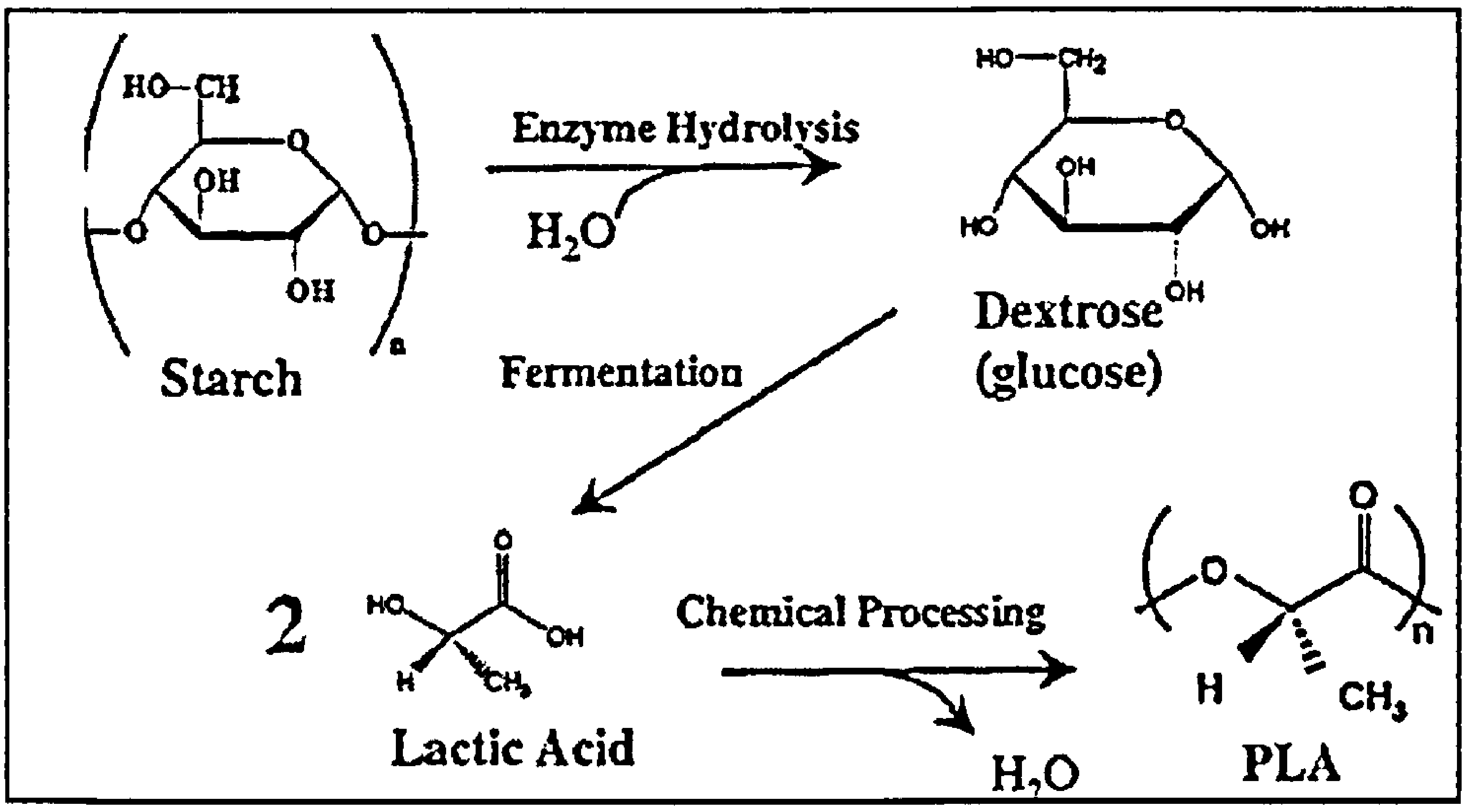


Figure 3.15 showing all the carbon in Nature Works PLA is derived from carbon dioxide [56]

3.3.4.7 Technical Performance of PLA

Technically, PLA films have the following valuable attributes for packaging applications:

- Good stiffness to enable down gauging
- Heat sealability at low temperatures
- Excellent gloss and clarity
- Good ductility and crack resistance and twist retention for hinges
- Barrier against flavour and oil
- Good processability and excellent printability

The elasticity module of PLA has been found to be higher than for other commercially avaible materials, which results in a reduction in wall thickness. PLA has been found to have limitations in terms of temperature durability and low impact properties.

PLA's physical properties are comparable to conventional oil-based plastics such as APET, PS and OPS. PLA's impact, rigidity, drawability and clarity properties are comparable to OPS, however PLA does have a natural yellow tint, which can be masked using a blue tint. PLA, like OPS, also requires edge heaters when thermoforming to prevent cracking during processing. PLA has a similar service temperature (below 60°C) and density (1.25 S.G) to APET. PLA requires drying before extrusion. Pactiv do not currently have these facilities and will therefore have to buy in film from a third party as they do with APET.

It is possible to process PLA using existing technologies, such as:

- Sheet extrusion
- Thermoforming
- Extrusion coating
- Non-orientated film extrusion
- Bi-orientated film extrusion
- Bi-axial starching
- Injection moulding
- Stretch blow moulding
- Fibre spinning

Cargill Dow currently have the following products commercially available for food applications:

A. Rigid Thermoforms, which feature:

    - Clear, short shelf-life, refrigerated trays and lids which can be used in applications such as fruits, vegetables and deli.
    - Opaque dairy containers for use in yoghurt, cheese and cream applications
    - Disposable articles such as plates and cups

B. Biaxially Orientated Films:

- Shrink wrap for consumer goods packaging
- Twist wrap sweets
- Laminations to paperboard for food packaging

C. Bottles for:

- short shelf life milk and oil packaging

3.3.4.8 Environmental Issues related to PLA

The environmental advantages of PLA over conventional oil-based plastics inlude:

1. It is derived from sustainable feedstocks (Genetically Modified (GM) crops today and biomass in the future).
2. The raw materials used are carbon netural (Figure 3.15)
3. Cargill Dow uses 20-50% less fossil fuel in production of PLA and greenhouse gas emissions are 60% lower with PLA than with traditional petroleum derived plastics [56].
4. PLA fits with all major waste disposal options including incineration, recycling, land filling and composting. Composting is their preferred option. PLA is compostable within industrial composting facilities and has approval from several European composting organisations [56].

PLA is designed to fit any waste management system. Traditional polymers are either recycled, incineration or sent to landfill, whereas PLA can go to all of the already mentioned, plus it can biodegrade by composting, anaerobic digestion or chemical recycling. This means that PLA is infinitely more flexible with respect to its disposal of it after it has fulfilled its useful purpose.

The biodegradation of PLA is a two-stage process: Firstly, the reduction of the molecular weight through a process of hydrolysis, from moisture and heat. Secondly, the digestion of low molecular weight species by micro organisms.

The rate of degradation is dependant on temperature, humidity and the availability of suitable micro-organisms. However, biodegradation of PLA requires specific conditions of high temperature (60°C) and moisture which can be found in municipal compost systems.

PLA is also designed for multi level chemical recycling, which is recycling back to the monomer from industrial and post consumer waste streams. PLA has a unique property: when used the polymer is combined with monomer, prime polymer can be produced. There does, however, need to be an infrastructure to collect and reprocess the used polymer.

Cargill Dow often find that pressure groups or NGOs (non-governmental organisations) are quite diverse and so are their opinions – some are favourable, others less so. Those with least favourable opinions are often least informed about NatureWorks, PLA, and its sustainability journey. To ensure that pressure groups understand Cargill Dow's position, they have committed resources to engage NGOs in dialogues and form stakeholder alliances to help them sort through the difficult issues as they arise in their business evolution. Cargill Dow and NatureWorks are in the early stages, so the impact has not yet been fully realised. Specific to the UK market, Cargill Dow have begun dialogues with Friends of the Earth and Greenpeace.

GMO's and Health and Safety Concerns on PLA, which is made from lactic acid, a naturally occurring compound found in food and the human body. Lactic acid is made from plant sugars (dextrose) by fermentation. Conversion of dextrose to lactic acid with subsequent conversion of lactic acid to PLA utilises high temperatures and numerous processing steps. Even though some of the corn may have initially contained GMOs, there is no corn DNA found in PLA pellets.
Cargill Dow is very open to influencing US agricultural practices by sourcing non-GMO corn for processing at Blair. They cannot guarantee that this corn will be utilised to produce a specific lot of PLA. Cargill Dow have set up an offset program, however they claim that "it is impossible to speculate on what is acceptable to others".

3.3.4.9 Cost Effectiveness of PLA

The product must be economically viable and hence the cost of material and processing must be weighed against the technical performances and the environmental benefits.

Currently PLA price varies between approximately 2.5 € and 3 € per kilogram and is more expensive that the current commercial oil-based materials as shown in Figure 3.16. The rework and scrap generated would have to be investigated, as the potential percentage of scrap is very high at 10-30% scrap.

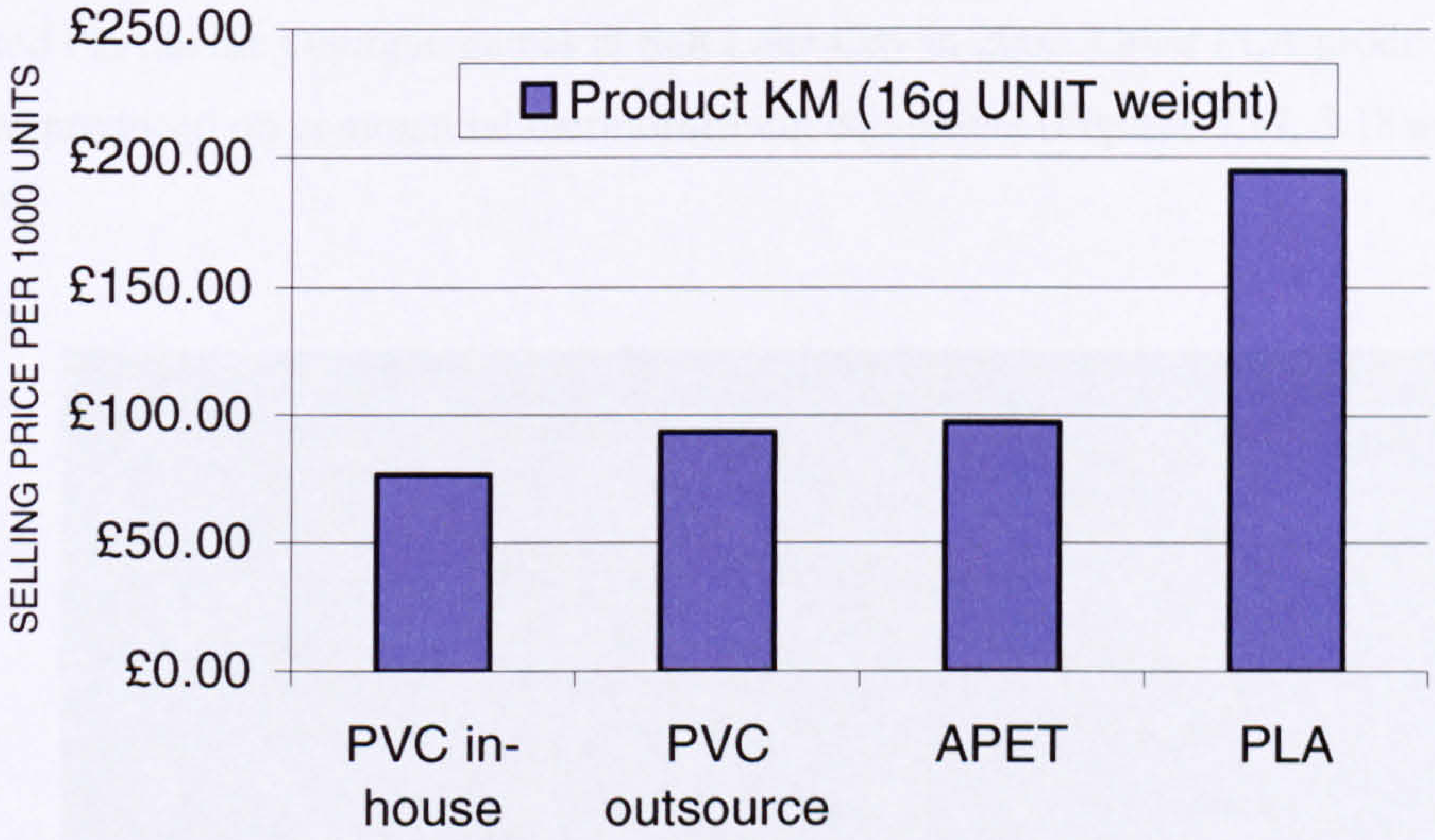


Figure 3.16: Comparison of worst case price implications using conventional plastics and PLA film form external supplier.

(The data is based on Pactiv's production of 1000 units of thermoformed trays).

PLA does, however, have massive scope to close this price deficit with conventional oil-based materials. The high rigidity of PLA can offer potential weight savings when compared to certain oil-based packaging materials. There is a huge potential for Pactiv to reduce costs by setting up rework loops for scrap material and by extruding in-house. Cargill Dow is also predicted to lower the selling price by leveraging economies of scale. For instance PLA has been accepted as biodegradable in the German waste system and has seen a marked decrease in tax from 1.5€ to 0.25€ per kg.

3.3.4.10 Examples of PLA Application in Food Packaging

There has been a rapid growth of PLA in food packaging. Coca-Cola successfully tested PLA at the Olympic games at Salt Lake City in 2002. Other PLA products have been produced on commercial thermoforming equipment (Figures 3.17, 3.18 and 3.19).

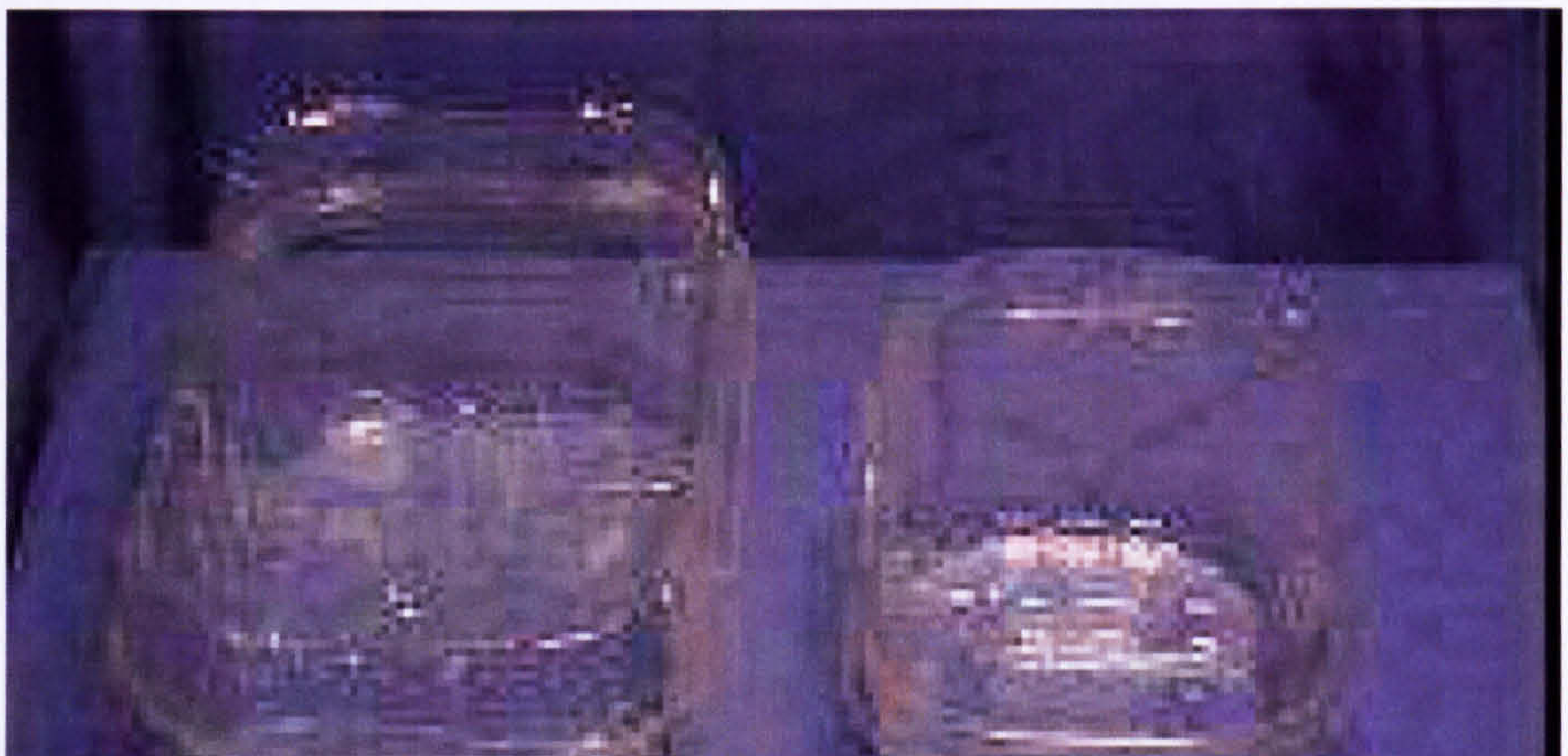


Figure 3.17: PLA fruit punnets (manufactured by Autobar)

Figure 3.18: PLA confectionery pack (manufactured by Pactiv)

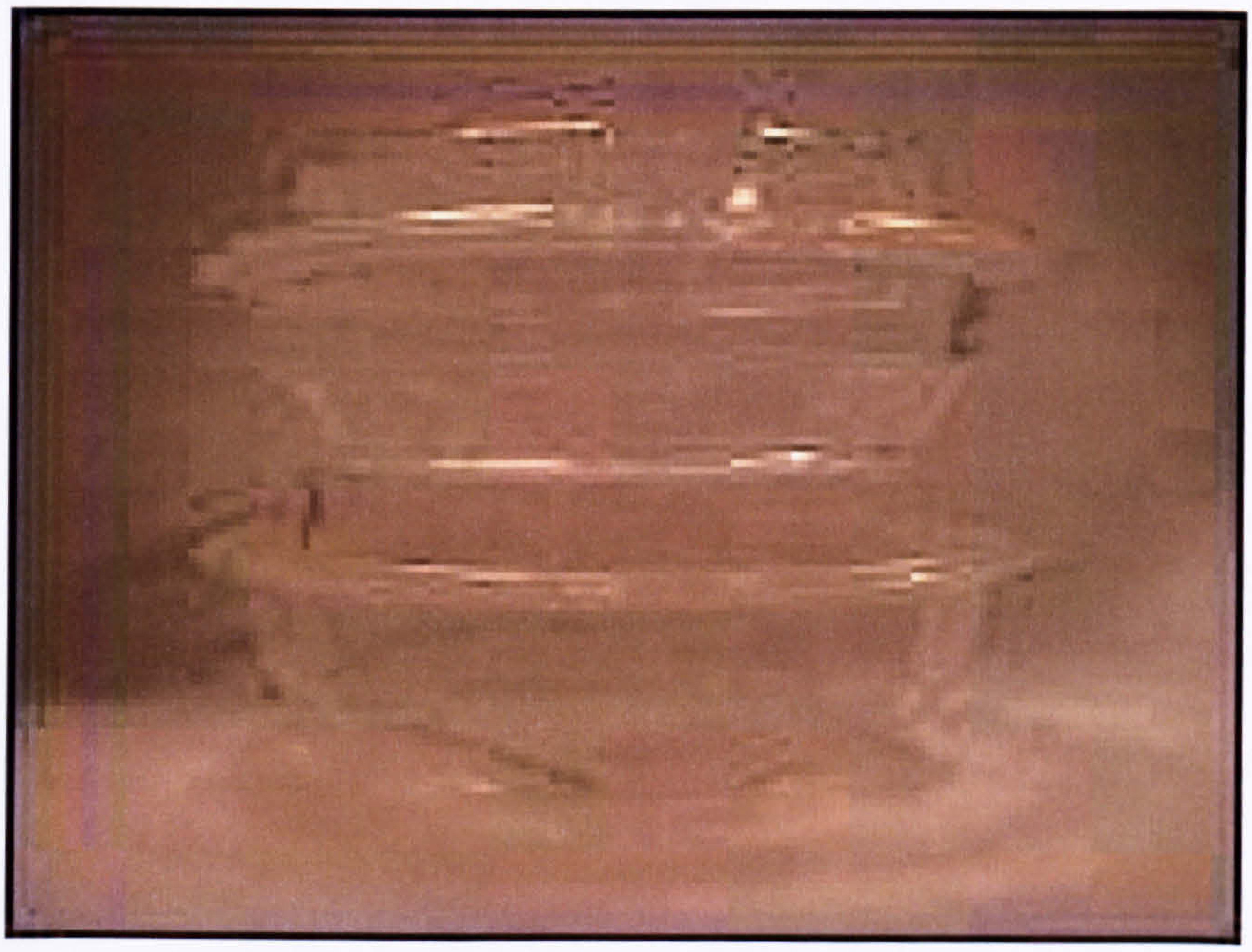


Figure 3.19: PLA Salad pack (manufactured by Pactiv)

3.3.5 Biopolymers from complex of starch and biodegradable polymers

Current manufacturers of biopolymers from complex of starch and biodegradable plastics include:

Novamont,	Materbi®	www.materbi.com
Rodenburg,	Solanyl®	www.biopolymers.nl
Potatopak,		www.potatopak.org
Greenlight,	Greenfill	www.greenlightproducts.co.uk
Biotec,	BioPlast	www.biotec.de
BIOP,	BIOPar	www.biopag.de
Amercian Excelsior,	Eco-flow	www.amerexcel.com
Japan Corn Starch,	Evercorn	www.japan-cornstarch.com

3.4 Standards and Certification for Biodegradable polymers

A definition of biodegradation given by the CEN (European Committee of Standardisation. "A biodegradable material is called biodegradable, with respect to specific environmental conditions, if it undergoes biodegradation to a specific extent within a given time measured by standard test methods and biodegradation is a degradation caused by biological activity especially by enzymic action leading to a significant change of the chemical structure of a material [57]."

A biodegradable polymer is a polymer that is capable of being degraded by microorganisms, such as bacteria and fungi. In order to be termed biodegradable, a material must lose both the mechanical and chemical identity of the polymeric starting material within a given time period [57]. To be designated as compostable, a materials has to biodegrade and disintegrate in a composting system under standard test methods.

In Europe, the criteria for biodegradability are set out in the European Standard EN 13432, 2000, which is binding when applied to compostable packaging under the EU Directive on Packaging and Packaging Waste (94/62/EC). Conformity to EN 13432 must be tested by accredited testing organisations with international experience in the specific sector.

The European standard EN 13432 states the requirements and procedures that packaging and packaging materials must fulfil in order to be defined biodegradable by addressing four criteria which must be met:

1. Biodegradability: More than 90% biodegradation must be achieved compared to standard cellulose. This must be achieved in 180 days under controlled composting conditions as stated in ISO 14855
2. Disintegration during biological treatment: More than 90% in 3 months as stated in ISO FDIS 16929
3. Effect on the biological treatment process: Absence of hazardous chemical.
4. Effect on the quality of the resulting compost: need to test for ecotoxicity, using a reference compost, for example a germination test

Composting is a potential disposal route for biopolymers. The four main types of composting are:

1. Aerobic windrow composting or open windrow composting: Waste is composted in controlled 'heaps' in the open air. These heaps are periodically turned until the waste is deemed to have turned into compost. This method is not suitable for the composting of food waste as sufficient temperatures are not reached. This is the most common form of composting in the UK[58].

2. In-vessel aerobic composting: This is similar to windrow composting, but in a closed vessel, which is a more controlled method. As such food waste may be composted provided it meets certain temperatures for a sustained time period. Invessel aerobic composting is commonly used as a sterilisation method prior to open windrow

3. Anaerobic digestion: Biological breakdown in the absence of oxygen. This often occurs in landfill anaerobic digesters. Methane generated needs to be controlled by minimisation of organic wastes into landfill, but it can be utilised as fuel if collected from anaerobic digesters.

4. Mechanical biological treatment (MBT): Waste is mechanically separated into compostable materials and the remainder is sent to landfill.

Biodegradable and compostable plastics are often required to be a direct replacement in terms of mechanical and physical properties, because they have better end of life disposal options they should be separated from the waste stream if they are not to be composted. Biodegradable polymers can be mixed with other compostable waste provided they meet the international standard (BS EN 13432:2000), which states that any material must be completely degraded after a set period of time at a set elevated temperature. However, they are difficult to distinguish from conventional oil-based plastics by appearance alone. Certification and labelling of biodegradable polymer products are therefore important to establish effective strictly regulated composting schemes. In the UK, all manufacturers of biodegradable materials are proposing to use the certification mark (Figure 3.20) from the DIN Certco certification scheme, administered by the composting association[59].

Figure 3.20: DIN Certo 'compostable' certification mark

3.4.1 Issues related to Biodegradable Packaging

- Renewable, rather than biodegradable maybe the key to implementing these polymers into the market place on a sustainable basis
- The packaging life cycle from cradle to grave is complex, and particular materials have advantages at different stages during the lifecycle. Therefore it could be argued that certain materials are better for certain interest groups. Plastic manufacturers for example, could claim that a polymer that uses less energy to manufacture would be preferable. However, it may not be the preferred material for end of life. Therefore an independent LCA body needs to be used, but industry will be wary of giving up the confidential information required to enable such decisions to be made.

3.5 Gaps and Obstacles for the Future of Biopolymers

Generally, biopolymers are being designed to replace existing materials used in packaging. Unless there are obvious benefits such as improved physical, mechanical properties or a reduction in price or even a government incentive, industry will not spend time and money retrofitting or replacing manufacturing equipment. Therefore more work needs to be done to produce cost effective biodegradable polymers with improved or at the very least equivalent properties which can be produced with minimum modifications of existing processing equipment.

Currently the packaging industry uses different polymers to fulfil different functions, for example PVC is used for its clarity and ability to withstand low temperatures such as the freezer, and PP is used for its ability to withstand higher temperatures such as in a microwave. A range of biopolymers needs to be developed to be able to cope with service temperatures such as these, so that designers and manufacturers can use biopolymers in all situations. Government intervention could encourage the use of biopolymers which would help to develop the industry further.

3.6 Life Cycle Assessment (LCA): Background and Methodology

The packaging life cycle from cradle to grave is complex, and particular materials have advantages at different stages during the lifecycle. Therefore it could be argued that certain materials are better for certain interest groups. Plastic manufactures for example, could claim that a polymer that uses less energy to manufacture would be preferable. However, it may not be the preferred material for end-of-life management. Therefore an independent LCA needs to be conducted to understand the environmental impact of replacing the conventional materials with biodegradable alternatives.

3.6.1 General Overview of LCA Method

Life cycle assessment examines and measures the environmental effects associated with a given product, from the extraction of primary raw materials, through manufacturing and its use and eventual disposal. It looks at all of the materials and processes involved, the products, wastes and co-products created, the methods used to treat wastes and the quantities of energy used [60].

LCA is a way of thinking about products and services, whilst considering the whole life cycle. It involves 'an evaluation to improve environmental performance in organisations'. LCA looks at the whole chain of a process. This can be described as 'cradle to grave analysis', 'eco-balance', 'resource analysis', 'environmental impact analysis'.

LCA is one of several tools which can aid in decision making whatever the application. For example, it can document existing product systems for information purposes and can implement changes to existing product systems, to improve them or to implement a new product system.

Life cycle interpretation is a systematic procedure to identify, quantify, check and evaluate information from the results of the (LCI) life cycle inventory analysis and /or (LCIA) life cycle impact assessment of a product system, and to present them in order to meet the requirements of the application as described in the goal and scope of the study. The practitioner undertaking the LCA study should be in close contact with the commissioner throughout the study to ensure that specific questions are addressed. This communication also has to be maintained throughout the life cycle interpretation phase to ensure essential transparency. Where preferences, assumptions or value choices are involved, these need to be clearly stated by the LCA practitioner in the final report [61].

Life cycle assessment (LCA) evaluates the environmental burdens associated with a product, process, or activity by identifying and quantifying energy and materials used, and wastes released to the environment. It assesses the impact of those energy and material uses and releases to the environment and identifies and evaluates opportunities to effect environmental improvements. The assessment includes the entire life cycle of the product, process or activity, encompassing extracting and processing raw materials, manufacturing, transportation and distribution, use, re-use, maintenance; recycling and final disposal[62]. This quote contains ideas, concepts and philosophies on sustainability. LCA illustrates the potential benefits that may be achieved in an objective route to sustainability.

Sustainability is a 'buzzword' within environmental circles. It is a compromise of many different definitions and therefore means different things to different people. In terms of the packaging industry it relates to a product that originates from a sustainable resource, as opposed to an un-sustainable resource such as: polypropylene, polyethylene (high and low density), polyvinyl chloride. Pactiv is now starting to look into other materials such as polylactic acid and starch based materials, which originate from sustainable resources.

LCA is a product of the academic environment it was developed in and therefore has many assumptions associated with it. The term 'life cycle assessment' was first used to describe holistic environmental assessment in the late 1980s [63]. This is shown by the assumptions and generalisations contained in the quote from SETAC [64]. These assumptions and generalisations are necessary when identifying and quantifying components such as energy and materials used. Also including waste products produced from a manufacturing process. This structured framework and objectivity of LCA is relied upon to give reliable comparisons of various types of recyclable, degradable and environmentally friendly packaging.

LCA highlights the importance of discussions about energy and material flows, showing the need for a more systems orientated approach. The recognition of LCA has grown over time as companies and individuals are being forced to be more aware of their waste and more environmentally conscious.

LCA dates back to the 1960s, and to energy analyses of industrial systems undertaken at that time and then subsequently in response to the oil crisis of the early 1970s. Although original emphasis was upon consumption of energy resources, a number of studies also considered emissions [65]. In the US, the Midwest Research Institute developed a methodology known as Resource and Environmental Profile Analysis (REPA), conducting its first analysis in 1969 on beverage containers for the Coca-Cola Company to compare different containers to determine which produced the fewest effects on natural resources and the environment [66]. This established the multi-criteria evaluation and 'cradle to grave' analysis for the environmental burden and impact of different product designs, their manufacture and disposal. As the discipline developed it was expanded and utilised as a tool to improve the energy efficiency of industrial systems in response to the oil crisis in the early 1970s. Despite this, interest in these studies declined in the late 1970s and it was not until the rise of environmental awareness in the 1980s that attention was again focused on LCA as a potentially valuable management tool. This was mainly due to improved consumer awareness of green issues at this time.

LCA is an analytical approach developed for quantifying the total environmental impacts of a product or process [67]. It therefore has the potential to be an essential tool for sustainability studies. The efficiency of each stage of a production chain is assessed in the move towards developing progressively and economically sustainable systems, ensuring that an activity meets the needs of the present without compromising the ability of future generations to meet their own needs [68]. When constructing an LCA the application and interpretation of the process should be put in the form of a logical block diagram. This is then used to ensure that the environmental burden of each component of a production chain is fully investigated and understood in turn. This helps to reduce the environmental burden of the chain as a whole, which in turn aids optimisation of the chain's environmental and economic performance. Figure 3.21 shows how energy and materials flow. A key is shown below the diagram indicating what function the various colours refer to. It is possible to view the entire system using figure 3.21. Any key areas are easily highlighted and can be dealt with. The affects of any changes can be seen throughout the systems very quickly. This is one of the major advantages that LCA has over more traditional process analyses, which tend to look only at the process under consideration in isolation, considering none of its associated processes.

Life cycle assessment studies begin with a goal then lead onto a definition phase and finish with an interpretation phase.

3.6.2 Defining LCA

Life cycle assessment can be defined as an essential tool or technique for the identification and reduction of the environmental burden of a variety of different production chains. This analytical tool maybe used to qualitatively and quantitatively assess the ratio of inputs and outputs for any given process in order to outline the most efficient product system or service from cradle to grave, identifying which has the least potential for environmental damage, highlighting potential environmental impacts such as global warming.

3.6.3 LCA Methodology

LCA methodology can be broken down into 4 defined stages:

- Goal and Scope are defined in relation to the application (ISO 14040)
- Inventory Analysis – involves the collection of data which is used to quantify the inputs and outputs of the product system
- Impact Assessment translates the inventory analysis results into environmental impacts
- Interpretation conclusions and recommendation are drawn from the inventory analysis and impact assessment results

3.6.3.1 Stage 1: Goal Definition and Scope

The different stages of an LCA must be defined at the earliest opportunity. Broadly speaking, the different stages should include the definition of goals for the study and its scope, an inventory analysis of each of the transfers or through flows, accompanied by an assessment of the impact that these have on the environment. The culmination of any study should be an improvement assessment in which alternative chains are reviewed and compared with a view to adopting the most sustainable option [69].

Goal definition, purpose and scope are essential to set firm objectives for the study and ensure a clear focus for the research. They also help to avoid subsequent misunderstandings about wider applications of the results when compared with similar but incompatible studies. Once the purpose of the study has been outlined, the scope must also be set. This involves defining the boundaries for the study that are relevant to its purpose [70].

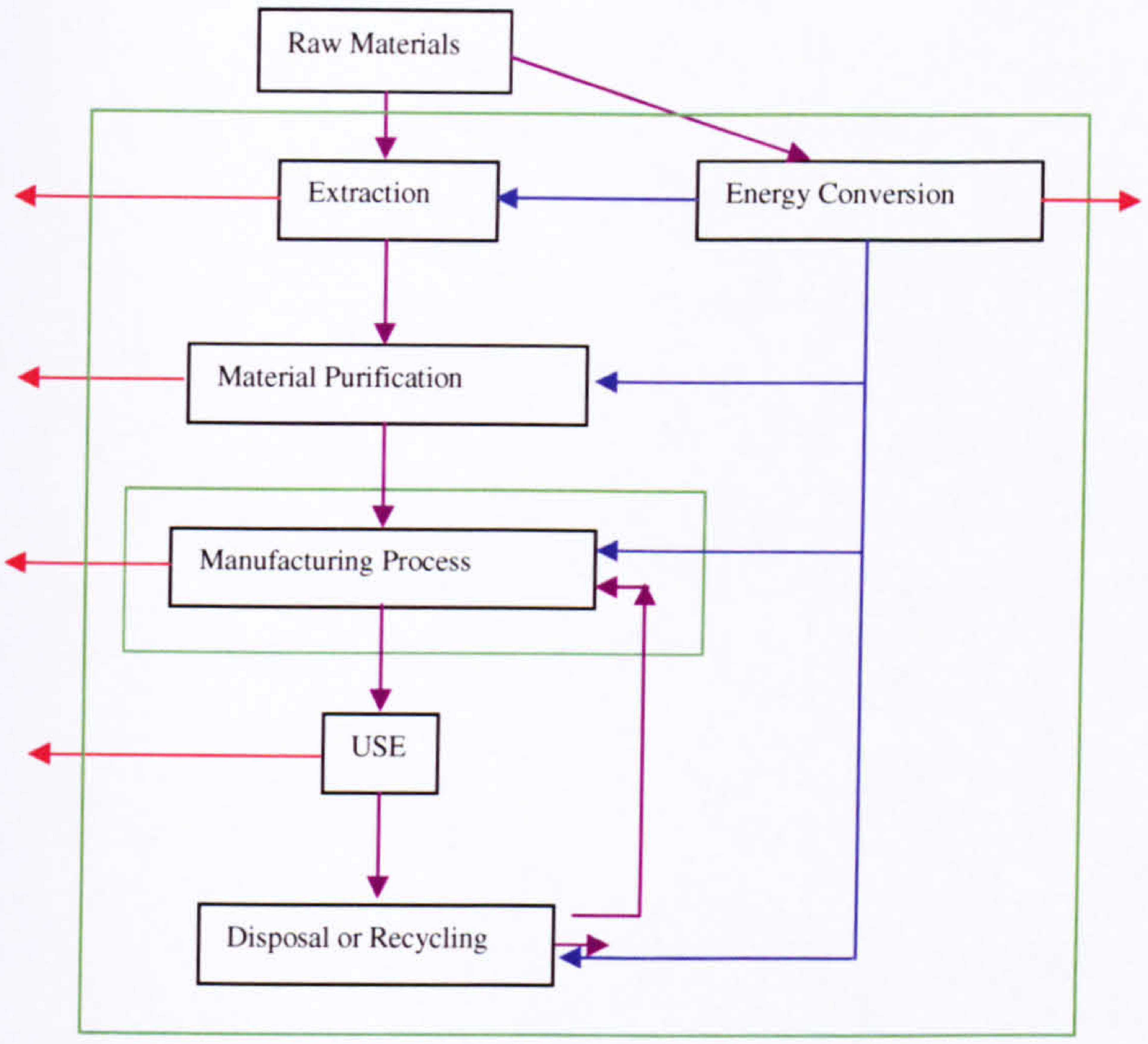


Figure 3.21: Flows of Materials, Energy, and System Boundaries in LCA [71].

Key for Figure 3.21
Green = Boundary lines
Red = Waste arrows
Blue = Energy arrows
Purple = Material arrows

These boundaries are shaped by the desired geographical applicability of the results, time horizons over which the analysis is relevant, and the focus of the study which may lead to omissions from the analysis of particular processes or stages of the life cycle [72].

A way of overcoming any debatable boundaries such as 'atmosphere' is to clearly define a functional unit, which in turn will be a measure of the systems performance. Having isolated the functional unit, it is necessary to make an inventory of each of the associated environmental burdens and quantify them. The material and energy inputs and product, waste and emission outputs to air, water and land must be isolated via a system orientated approach and quantified as they cross the systems boundaries. When doing this it soon becomes clear that this is entirely judgement based and is very much dependent on the positioning of the boundaries. Once identified and collected, input/output data for all of the subsystems of a process must be included in the functional unit to fit the constructed model [73]. The results are tabulated in order to assess their environmental impact. This again is a generalisation and highly dependent upon the judgement of the individual. The impact assessment is then achieved by normalising the aggregated data against the environmental impact data. To conclude the LCA a review and improvement assessment is carried out to determine the options for reducing the environmental impacts of the functional unit. This highlights that LCA is based upon a great deal of judgement from the individuals carrying out the research regarding which option has the lowest environmental impact.

3.6.3.1.1 Goal Definition

The purpose of goal definition is to clearly state the LCA objective, the reasons behind the objective, the project initiator, the practitioner and its intended audience, including a justification for the use of the LCA environmental assessment tool.

3.6.3.1.2 Scope

Scope is where the system boundaries are defined and other requirements for the study such as the inputs, processes, boundaries and outputs are set, stating simplifications and assumptions used.

3.6.3.1.3 Data Requirements

This includes the types of data to be collected, the quality of the data, and the data collection process. Data are usually collected in three categories: physical inputs, energy and raw material inputs, products and emissions

3.6.3.1.4 Functional Unit

The functional unit is the unit of analysis for the study and it provides a basis for comparison if more than one alternative is being studied. The functional unit should be defined in terms of the services provided by the product, process or activity under analysis and the definition must relate to the LCA objective. When making a comparative LCA it is imperative that the function, functional unit and reference flow of each product is equivalent in order to generate unbiased results. The functional unit is always expressed in SI units. [74]

3.6.3.2 Stage 2: Inventory

At the inventory phase, the environmental interventions associated with the life cycle for the functional unit are collected, quantified and collated. These are the material and energy inputs and product and emission outputs to air, water and land. A boundary is drawn around the system under analysis and the inputs and outputs, which cross the boundary are quantified. In an LCA, the material and energy flows should be drawn from the environment or discarded into the environment without human transformation (ISO 14040). The overall product system should extend upstream to primary resources, and downstream to the point where material is emitted into the environment so that it is dispersed in an uncontrolled way. LCAs that do not encompass this entire life cycle from ‘cradle-to-grave’ are called ‘cradle-to-gate’ analysis. The inventory stage is described in the international standard ISO 14041 and comprises of three stages: data collection procedure definition, data collection and inventory results calculation, see figure 3.22.

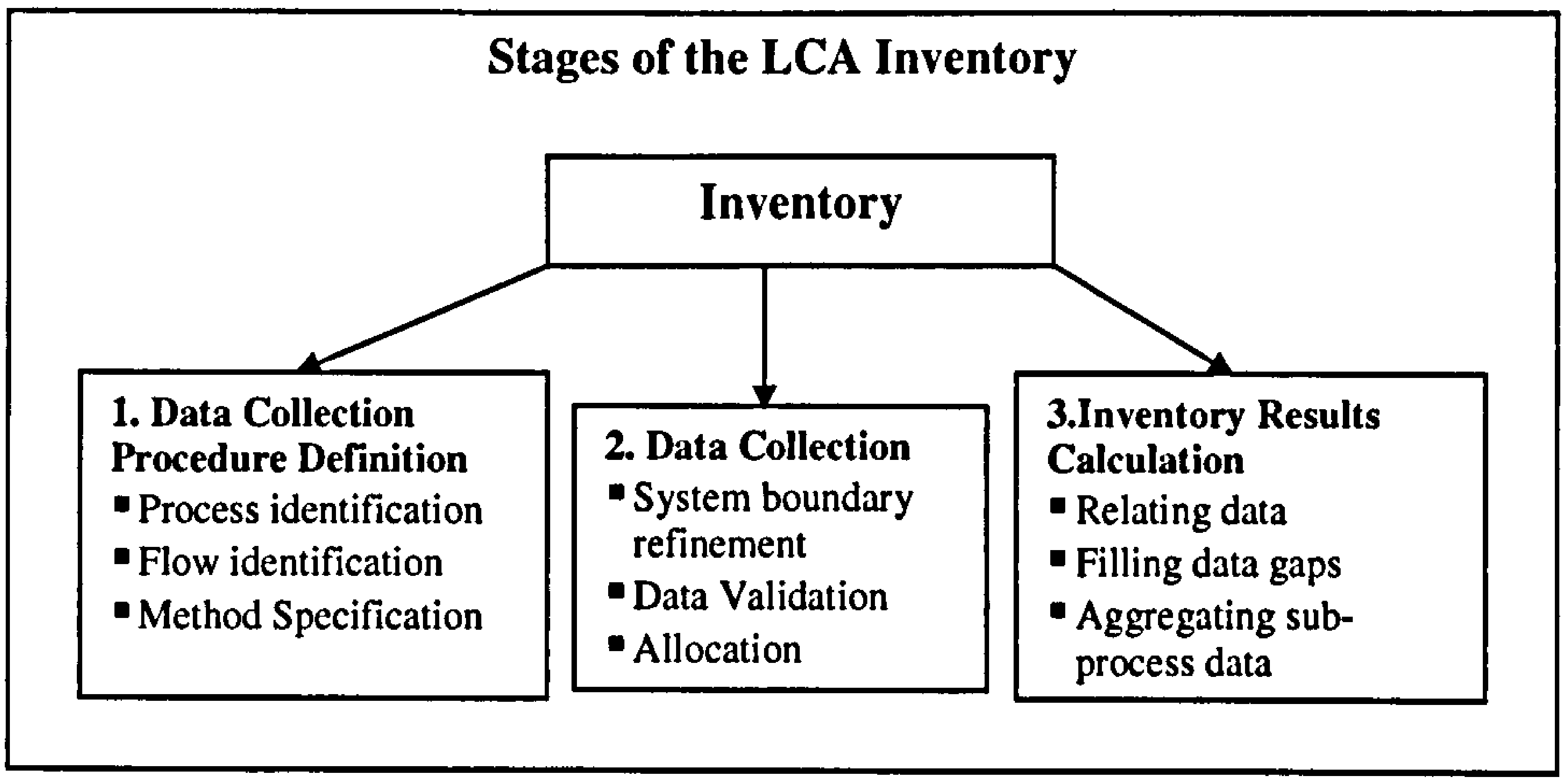


Figure 3.22: Stages of the LCA Inventory [74].

3.6.3.2.1 Data Collection procedure

Prior to data collection the following procedure should be followed:

- First identify the system processes. It can be useful at this stage to draw a boundary that makes a distinction between the 'foreground system'-the system under analysis and the 'background system.' The foreground system is "the set of processes whose selection or mode of operation is affected by decisions based on the study [75]." The background system is "all other processes which interact directly with the foreground system, usually by supplying material or energy to the foreground receiving material or energy from it [75]."

- The second stage is to ascertain the nature of the environmental flows allocate the raw materials and energy being input and the emissions to air, water and land. ISO 14041 refers to these environmental flows as interventions, and it is the linkage of the processes and environmental interventions that is referred to as the system boundary [76]. Process flow diagrams are often drawn to highlight the necessary data collection that must take place. This data is either primary data collected from the individual company audits, or secondary data which are often industrial averages. Allocation is necessary as unit processes are often not linked in simple linear chains.

3.6.3.3 Stage 3: Impact Assessment

The environmental interventions calculated in the analysis are translated into environmental impacts during the impact assessment phase of LCA (LCIA). The objective of this phase is convert huge volumes of inventory results into environmental impacts that can be understood by the users of the study results. These environmental impact categories allow the evaluation of product systems highlighting their significance.

3.6.3.3.1 Elements of the Impact Assessment Phase

The impact assessment phase of LCA consists of several mandatory and optional elements. The mandatory elements include impact category definition, classification and characterisation (Figure 3.23). The optional elements include normalisation, grouping and weighting, which are useful when conveying results to the intended audience. LCIA models such as ECO-Indicator 99 are often used in conjunction with LCA software to make these calculations.

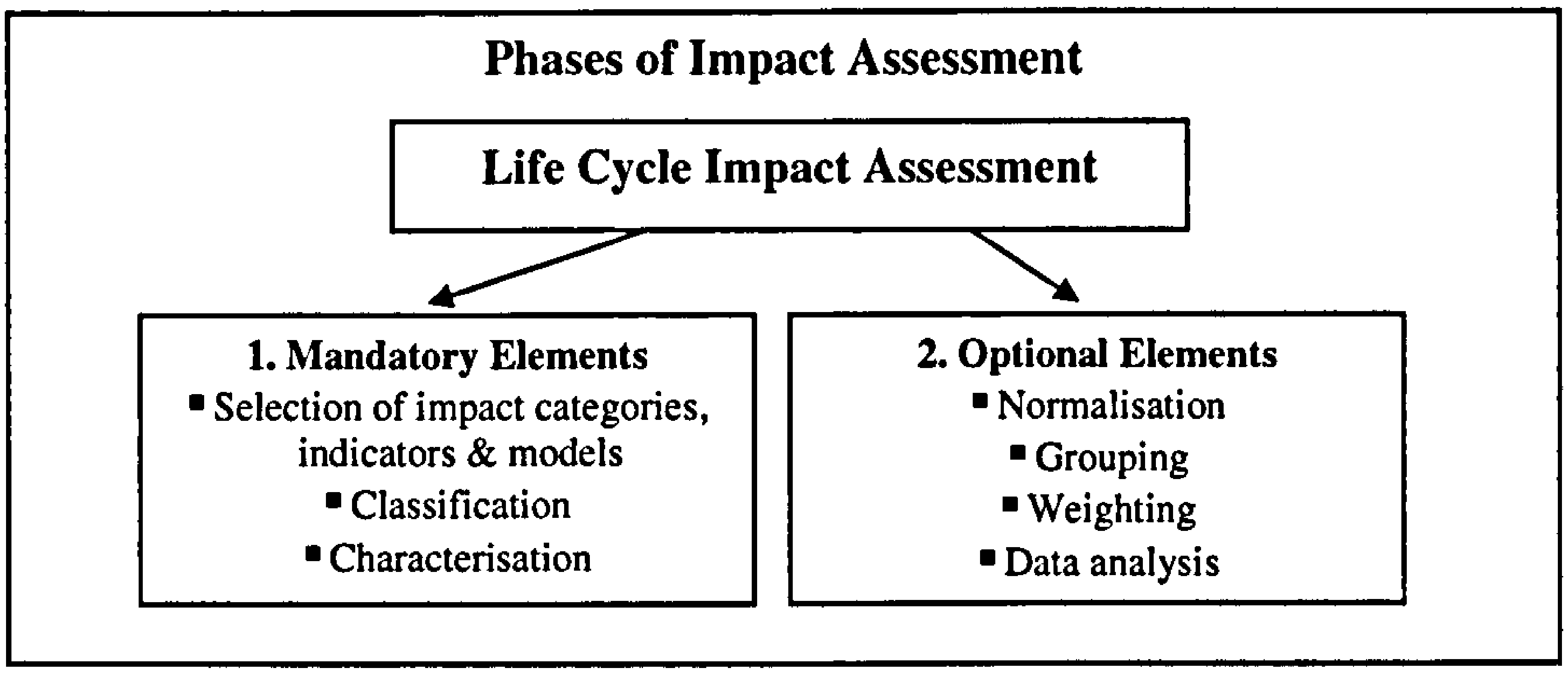


Figure 3.23: Phases of Impact Assessment

3.6.3.3.2 Selection of impact categories, category indicators and characterisation models

The selection and documentation of environmental impact categories is required in the goal and scope phase. These impact categories vary from climate change to ozone depletion, to human toxicity and land use. The environmental impacts in each category are quantified using category indicators. There are no compulsory impact categories with ISO 14042, however baseline categories are often used. In CML 2001 these baseline categories include abiotic resource depletion, biotic resource depletion, global warming potential, stratospheric ozone depletion, acidification, human toxicity, eco toxicity, photochemical ozone creation, eutrophication and solid waste generation.

3.6.3.3.3 Classification

The classification element aims to assign the inventory environmental intervention data to impact categories. Each intervention is linked to one or more types of environmental impact category (Figure 3.24).

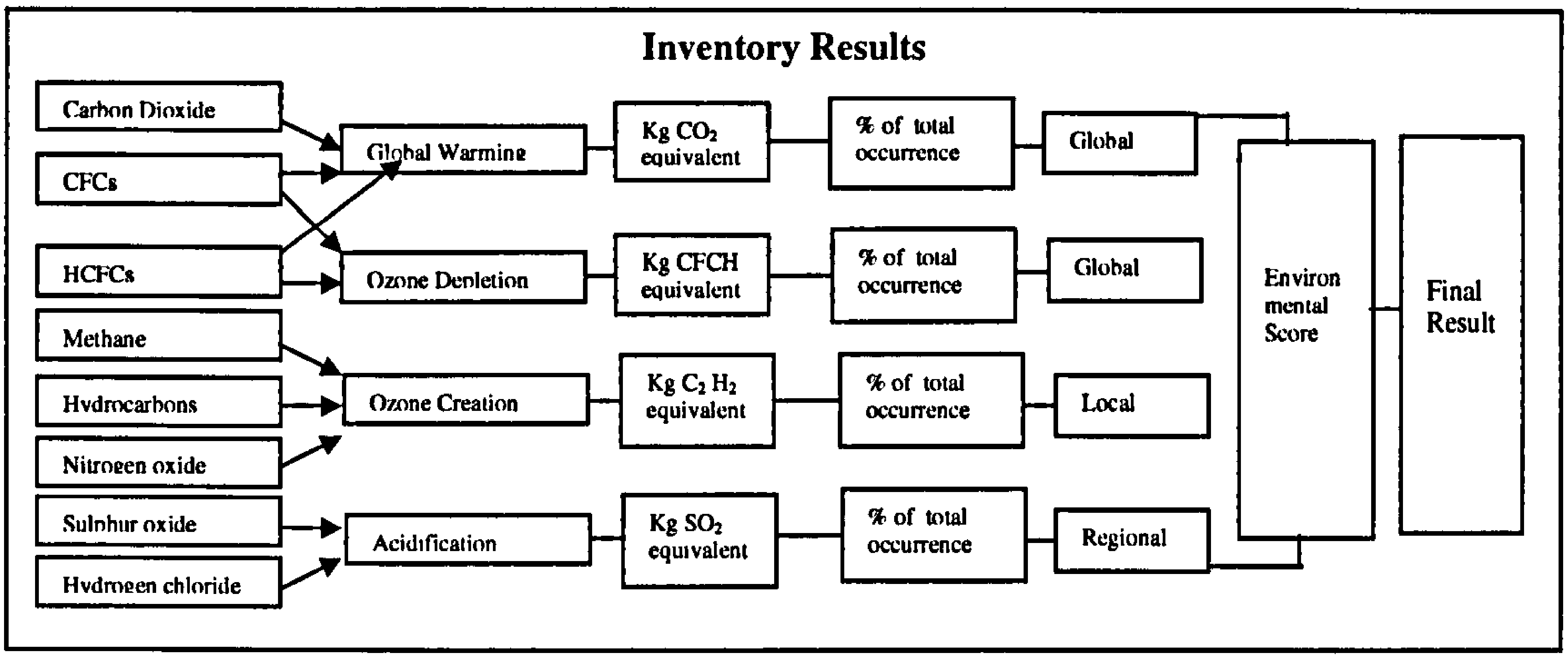


Figure 3.24: Phases of Impact Assessment

3.6.3.3.4 Characterisation

The characterisation component involves the quantification of impact categories, multiplying each intervention by a relevant weighting factor. This weighting factor is called the characterisation factor, assesses the contribution of each intervention to any one-impact category. The characterisation element is required to take account of the relative importance of each inventory result for a specific impact category.

3.6.3.3.5 Optional Elements

The optional elements, ie: normalisation, grouping, weighting and data analysis can be used individually or in combination with each other. These optional elements can increase the relevance of the results but there is no standard format for impact assessment and all are based on value judgement rather than scientific knowledge and expertise and are therefore very subjective.

The results are normalised in order to obtain an estimate of the relative significance of the results in each environmental impact category. The normalised score is then considered alongside the normalised scores for other impact categories in order to gain an impression of the relative contribution made by the system to each impact category within a given geographical area.

The next stage is grouping, which involves sorting and/or ranking the impact categories. Sorting involves grouping the impact categories on a nominal basis, for example, global, regional and local impacts. Ranking involves establishing a hierarchy among the impact categories, for example, high, medium and low priority. The normalised result for each impact category is multiplied by a weighting factor representing the relative importance of the different impact categories. Weighting however raises subjectivity, as there is no scientific basis for assessing the relative importance of impacts such as climate change and ozone depletion. The three main approaches to weighting are:

- Financial valuation: Each environmental impact is costed in conventional financial terms and is given an estimated external cost
- Social prioritisation: Multi-criteria analysis is used to measure social properties and derive relative weighting factors for the different impact categories
- Distance-to-target: Political targets are established for improved environmental performance and the impact categories are weighted according to the difference between current and target performance

Data analysis provides a better understanding of the reliability of the results from the impact assessment. Sensitivity analysis is most commonly used to investigate the sensitivity of the results to changes in LCI data.

3.6.3.4 Stage 4: Interpretation

The final phase of an LCA is the interpretation phase. During this phase, the results of the analysis are discussed and opportunities for reducing the environmental impacts associated with the functional unit are identified and evaluated. ISO 14043 states that this phase should evaluate the completeness, accuracy and robustness of the results with reference to methodological assumptions made in the goal and scope phase "in a form that is both comprehensible and useful to the decision maker."

3.6.4 Pros & Cons of LCA

LCA is a tool which has the greatest potential to help answer questions about sustainability and environmental burdens associated with the packaging industry. The technique requires quantifiable data of all inputs and outputs of a system. In order to achieve this, all of the components of an LCA must be known and all boundaries and characteristic energy and material flows identified in order for the environmental burden of the product or process under investigation to be quantified. This is not always possible with the food packaging industry.

The myth that an LCA is constructed in a sterile academic environment, free of bias from external driving forces and therefore produces results that are transparent, objective and can be easily transposed to the 'real world' must be stopped. It is possible that various educated people might use LCA as a decision support tool, but the value of LCA as a decision support tool is undermined by the potential for the bias, which may be introduced for any number of reasons.

The possible consequences of a biased indicator selection can be seen in the divergence and differing results of many LCA's, which set out to assess the same processes. This was clearly shown by the presentations given on the short exercises during the LCA module. Another example is the study on cloth reusable nappies and disposable nappies. Procter and Gamble sponsored a study which resulted in reusable nappies using more energy than their disposable counterparts, whereas a later study by the US National Association of Diaper (American word for 'nappy') Services showed that disposables consume 70-80% more energy [76]. This was later put down to the 'functional unit' and the boundaries of the system being investigated were different [76]. This highlights that the valuation stage of LCA is very subjective and the results depend on the values used, therefore giving rise to consumer suspicion regarding the validity of such 'objective' studies.

It is therefore imperative that if LCA studies are to be taken seriously, there needs to be some control on the values and boundaries being set. There is considerable scope for biasing the final results by selecting boundaries favourable to the preferred results [76]. Comparisons of the results are only possible if the study assumptions have been handled as uniformly as possible [76].

3.6.5 Conclusion of LCA

LCA can be used for decision-making, operational and strategic and awareness raising. The development of the International Standards on LCA is evidence that LCA is maturing as an environmental management approach. However due to LCA requiring an analyst to make value judgements and generalisations at every stage of the assessment, it is very open to abuse and can lead to mistrust in its results. This reduces its value as an environmental management tool. The nature of environmental legislation is that laws must apply to a diverse range of different practices and processes over space and time, whilst ensuring that all actors can see relevance in rulings and are bound by the legislation. This is therefore perfectly suited to the LCA approach, however the problems of bias must be overcome.

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CHAPTER 4: REDUCTION OF ENVIRONMENTAL IMPACT FROM PACTIV'S PRODUCTION

4.0 Reduction of Environmental Impact from Pactiv's Production

Chapter four provides an overview of Pactiv Corporation, highlighting that it is a market leader in the food packaging market and detailing its product range and accolades. The chapter demonstrates how this research project has been instrumental in reducing Pactiv's environmental impact during the fabrication of food packaging, by improving working practices, material utilisation and the technologies used. All of the projects undertaken entail sufficient cost savings to be commercially viable for Pactiv and are crucial to the continued competitiveness of the organisation.

4.1 Introduction to Pactiv and its environmental concerns

In 1999 Tenneco Packaging broke away from its sister company Tenneco Automotive to form an independent company: "Pactiv Corporation". Pactiv Corporation is now a leading producer of specialty packaging products, with sales exceeding $3 billion, 15,500 employees and 100 operations in 17 countries worldwide. Pactiv is the market leader in three growth sectors of the packaging industry: Consumer products (with the Hefty® brand), Food service/ Food Packaging and Protective and Flexible Packaging. With the broadest range of products in the speciality packaging industry, the company derives more than 80% of it revenue from market sectors in which it holds the number 1 or 2 position.

Pactiv's role in the speciality packaging industry is to manage complexity across the supply chain. Pactiv meets the market's demand for a broad product line, with a unique ability to deliver multiple products on a single truck, which entails extraordinary value in one simple package for end users and customers.
Pactiv Corporation's vision is to "Become the world's packaging specialist."

Hefty® is one of America's most trusted and respected brands. It is the leader in the following market segments: the high growth drawstring segment of the waste bag market, the slider bag segment of the food bag market, disposable tableware and disposable aluminium cookware.

Pactiv's development teams in USA market more than 50 new packaging products every year across speciality sectors, helping its customers differentiate themselves and supporting their expansion.

Over recent years, Pactiv has experienced rapid growth: In 1995 sales were $2 billion, 70% of which were paperboard, with 13000 employees spread across 80 sites, mainly in the USA. By 2001 sales had risen to $ 3 billion, 80 % of which were plastic, including speciality packaging (Figure 4.1). Pactiv now has 15,500 employees spread across 100 sites worldwide.

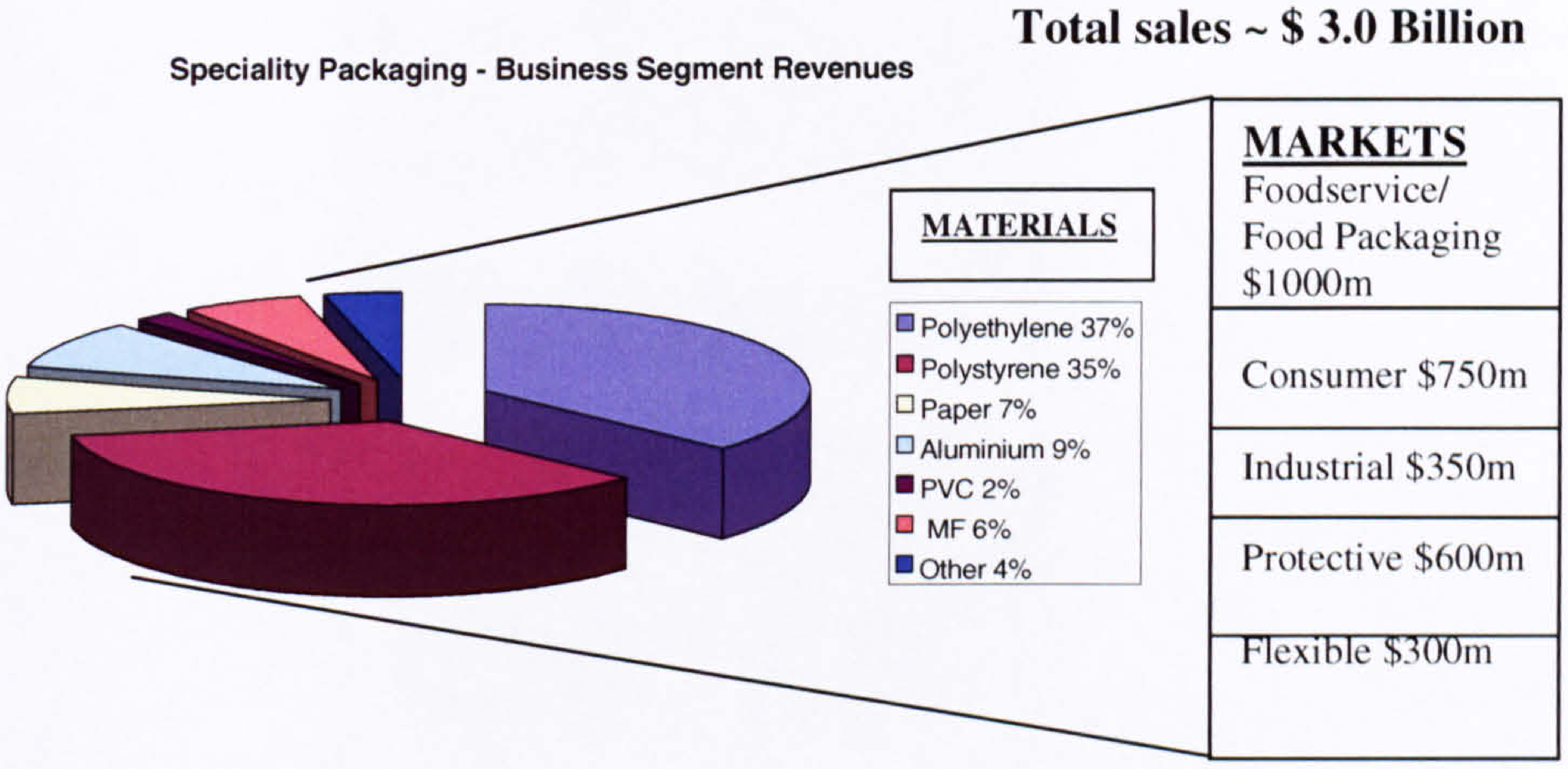


Figure 4.1: Shows Business Segment Revenues from Speciality Packaging [1]

The Pactiv Corporation has made 9 acquisitions since 1995, adding $2.2 billion in revenues. These include: Mobil Plastics, KNP –BT, Penlea & Delyn, Hexacomb, Amoca Foam Products, Champion Pressed Paperboard, Richter Manufacturing and Sentinel.

Pactiv has a unique ability to deliver multiple products through several channels to meet multiple customer needs in an integrated manner. By leveraging scale, technology and the skills of its personnel, Pactiv has emerged as an industry cost leader. The markets Pactiv serves are large, fragmented and growing at nearly double the rate of the packaging industry as a whole.

Pactiv Corporation accomplishments include:

- Hefty® The Gripper™ waste bags (Figure 4.2) were introduced with a patented Stretch and Grip Top™ that stretches easily around a dustbin rim and stays securely in place.

Figure 4.2: Hefty 'Gripper' waste bags [1]

Hefty® One Zip® slider bags (Figure 4.3) were renowned for the Arthritis Foundation "Ease of Use" commendation program through 2001. The slider bags received "Best of Show" from the American Culinary Institute.

Figure 4.3: Hefty 'one zip' sandwich, storage and freezer bags [1].

- Pactiv was ranked 13th out of 100 top suppliers in 2001 by SYSCO®, North America's leading marketer and distributor of food and food service products.

- The Sarento® cheese package with the Hefty® Slide-Rite® system was awarded first place in the food category of the Institute of Packaging Professionals' AmeriStar packaging competition in 2001.

- The Food Service and Packaging Institute named the following Pactiv products "best in class" for 2000: SmartLock® foam take-out containers, Traymate® foam trays with clear plastic domes, Chicken Barn^{TM} containers with handles, and Black and Gold Classic Carry-Out® aluminium containers.

- Slide Rite® air cushioned utility bags (Figure 4.4) were named one of the top 50 products for 2000 by Packaging Digest.

Figure 4.4: A 'slide rite' air cushioned utility bag [1]

Pactiv Europe's medical business, which manufactures products for medical packaging and operating drapes and gowns, joined forces with U.S Rollprint Packaging Products, Inc. to create a global strategic partnership for medical packaging.

- The Pactiv Propyflex^{TM} PVC – free medical bag won the Medical Design Excellence Award in 2000.
- ClearView® Meal Master ^{TM} Chicken Roaster Container with Smart Tote ^{TM} Handles (Figure 4.5).

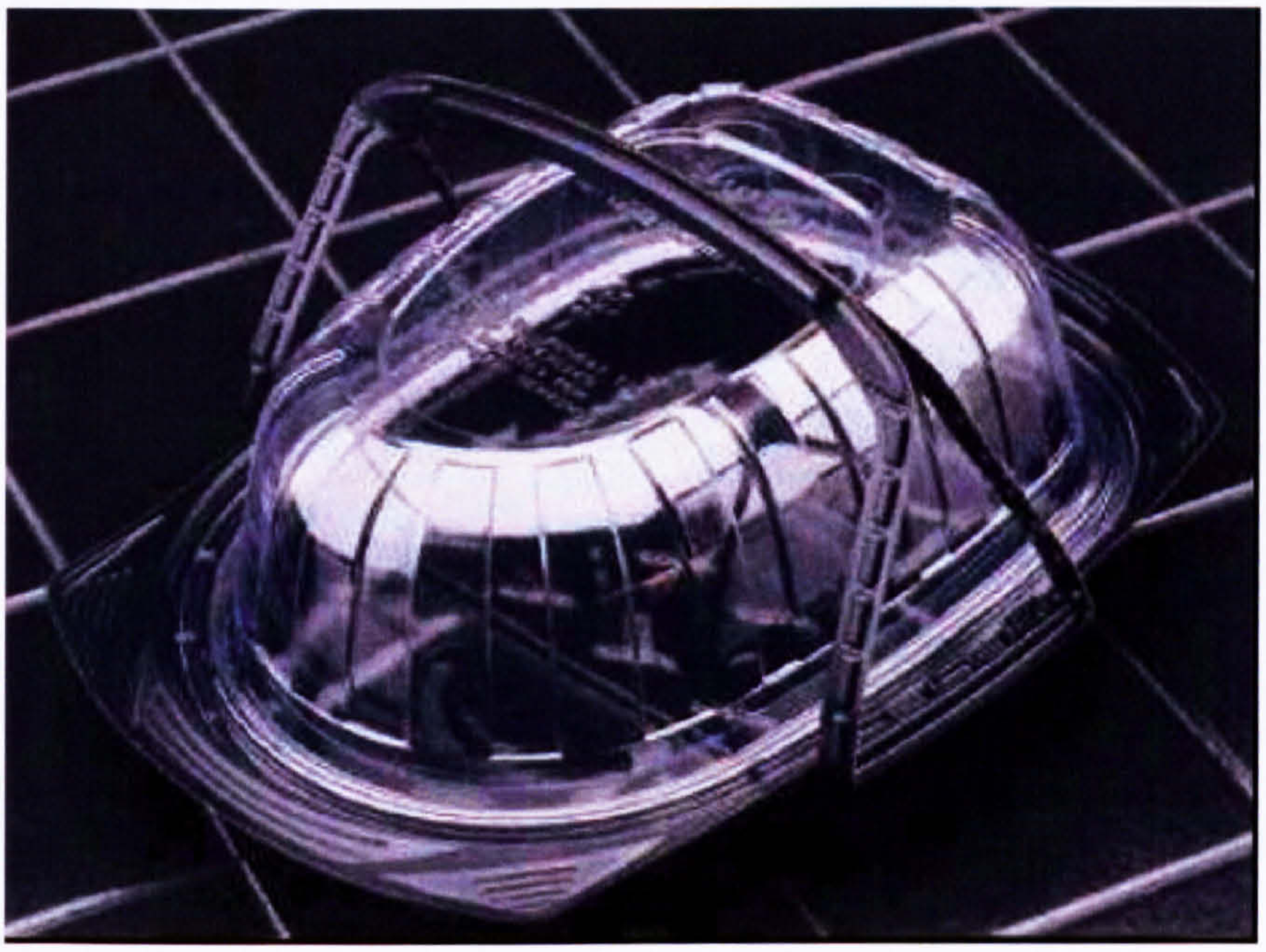


Figure 4.5: The chicken roaster container [1]

The Chicken Roaster Container (Figure 4.5) offers multiple benefits. It enables the safe transportation of hot food, with Smart Tote handles. It is leak resistant and easy to assemble, with a 360° snap-in deli seal. The Smart Vent steam release system allows steam to vent and helps reduce condensation, even while stacked. Containers can be stacked up to three high (Figure 4.6).

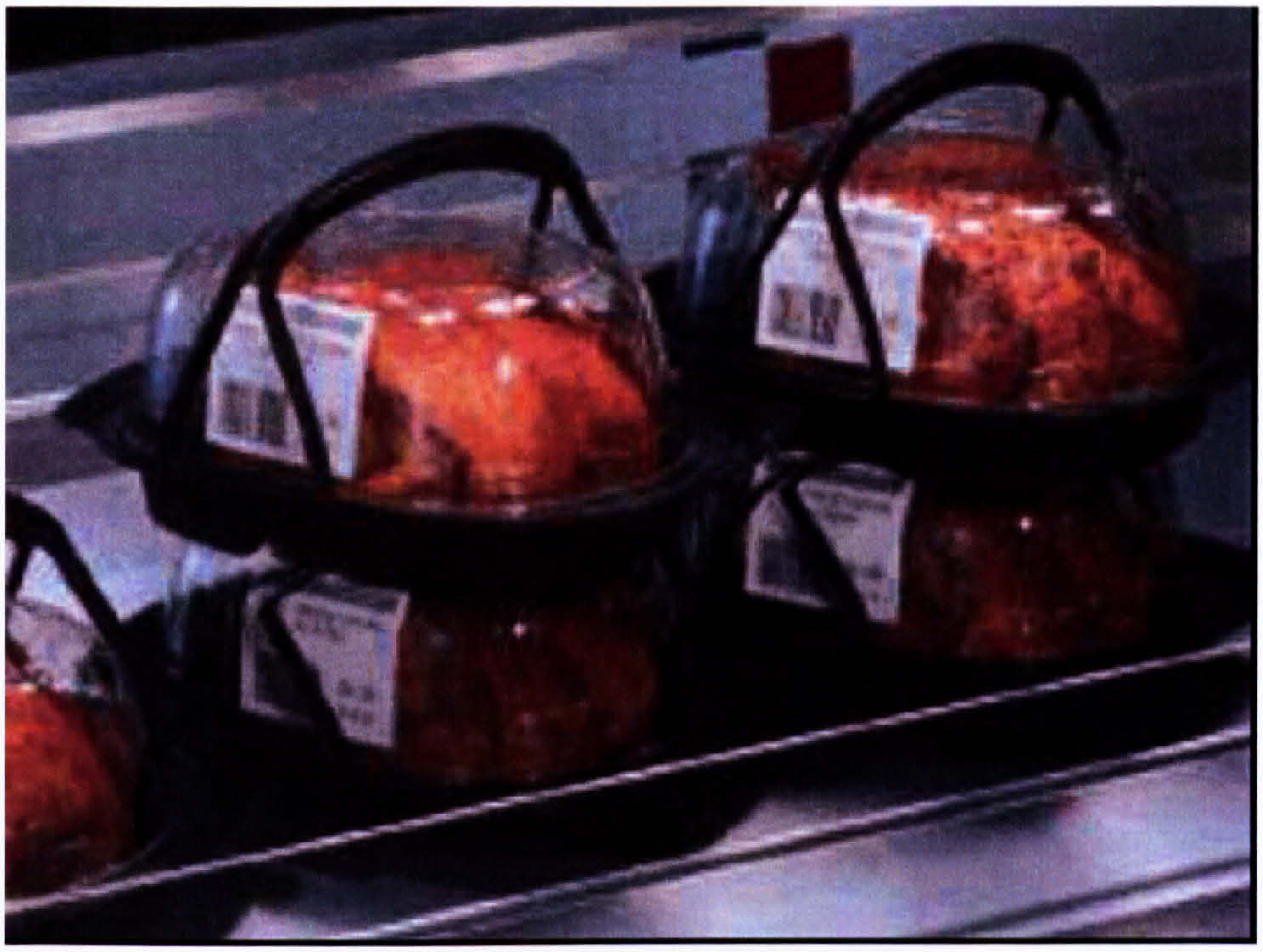


Figure 4.6: The chicken roaster container in use demonstrating that it is stackable [1]

The wide sidewall construction offers superior strength resistance, with flat walled sidewalls for labelling. The container offers exceptional temperature endurance, maintaining product integrity for up to 4 hours in the hot case. The microwaveable, ribbed bottom base enables customers to reheat the chicken, whilst keeping grease and excess liquid away from the chicken.

- Pactiv's Food Containers Range and Bakery Range.

Figure 4.7: Pactiv's food containers range [1]

Pactiv's general-purpose containers are ideal for presenting a wide variety of products. The existing range includes divided packs, bowls, lidded packs with and without snack forks and hinged containers with an integral seal to prevent leakage (Figure 4.7). The strong ribbed design boasts a positive stacking feature to maximise shelf utilisation.

Within Pactiv's Bakery and Containers range is a new selection of bakery packs offering a stylish, low cost packaging solution for a wide range of patisserie and bakery products (Figure 4.8).

Figure 4.8: Pactiv's bakery range [1].

The containers are made from customer friendly clear plastic materials and have been designed for central bakeries and in store operations. Products are well protected and displayed to their best advantage.

Pactiv Corporation today is a unified company with common goals incorporating core competences, with excellent service. Its market position offers potential for growth and product development. Pactiv's European strategy involves applying and benefiting from the synergies enjoyed by its US division to offer a global service and target a global leadership position.

Figure 4.9 shows how Pactiv Europe fits into the overall Pactiv Corporation.

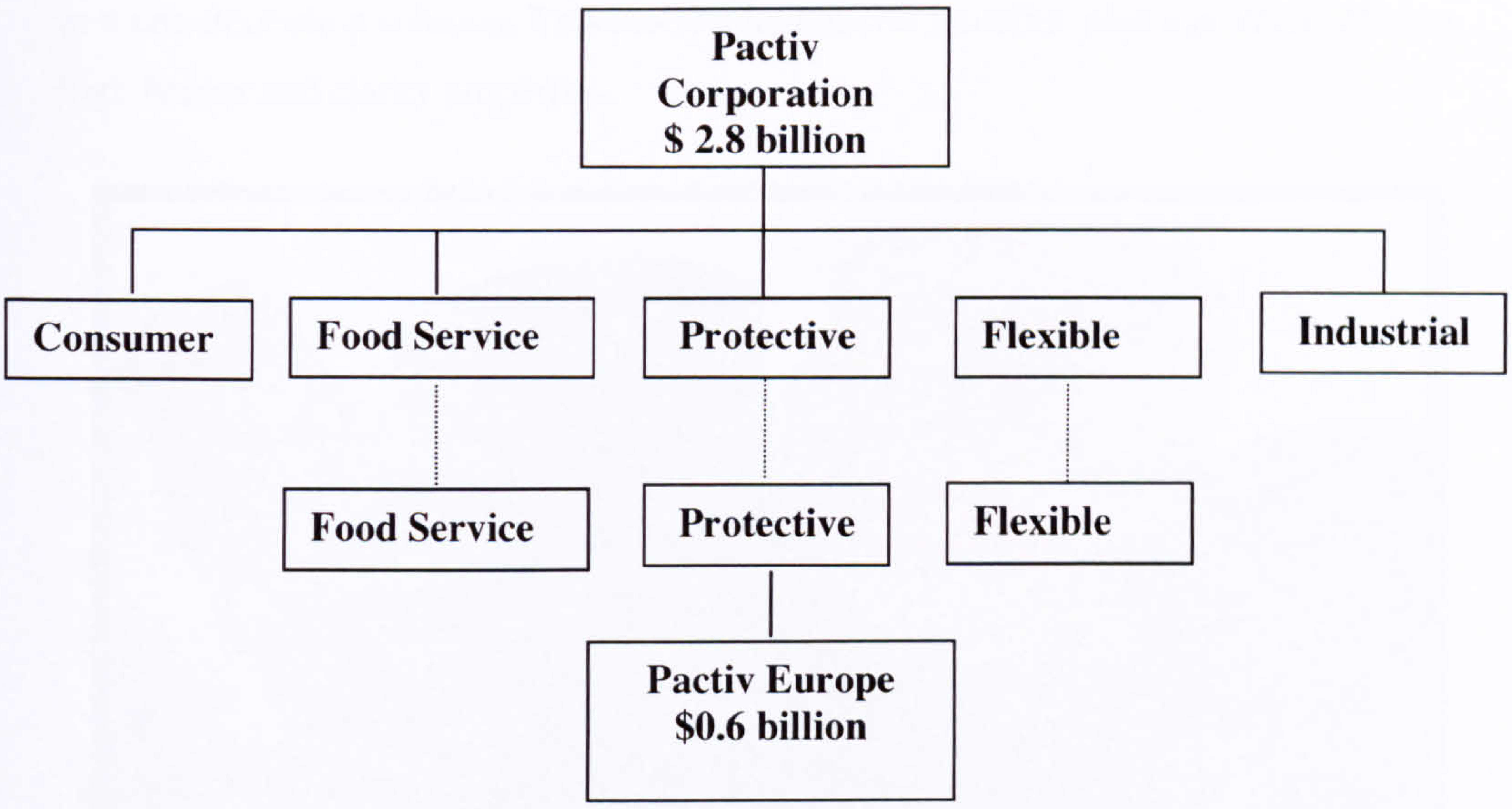


Figure 4.9: Pactiv Corporation including Pactiv Europe [1].

Pactiv Europe's philosophy is to be 'one step ahead' in terms of solutions, service, reliability, innovation and speed. It currently leads two of its markets and occupies second place in a further four markets, as demonstrated in Table 4.1.

Table 4.1: Pactiv Packaging Europe (PPE) market positions [1]

	Market Coverage	*Position*
Protective Packaging	Europe	1
Detergent Packaging	Europe	1
Diaper Over wraps	Europe	2
Egg Packaging	Europe	2
Operating Drapes	Europe	2
Thermoformed Packaging	UK	2

An example of a new Pactiv product is the 'Top Web Seal' (Figure 4.10), which has been a joint development between the thermoforming and Flexible divisions, resulting in a one-door-shop solution. This has resulted in cost benefits, plus a product offering high barrier and clarity properties.

Figure 4.10: Examples of Top Web Seal [1].

The UK part of Pactiv Europe had an annual turnover of $80 million (£56.28 million) at today's exchange rate, with profits of £2.2 million which is a 33% improvement on the previous year. The UK Pactiv thermoforming factories employ approximately 600 people spread over three sites: Caerphilly, Livingston and the main site Stanley (which is where the Research Engineer is based, although managing projects and travelling between the other two sites).

Pactiv Europe also has operations in Denmark, Holland, France and Spain. Pactiv is looking to expand in these locations to improve distribution for food process products in mainland Europe (see Figure 4.11 a map of Europe, detailing it's activates). These should be fully functional within 3 years, with products originating from both the UK and the US.

Figure 4.11: Pactiv plants and locations across Europe [1]

Pactiv UK produces thermoformed products of which 80% are customer specific/bespoke. Pactiv has in-house designers, tooling and manufactures to meet those demands. The remaining 20% are standard products. Pactiv UK currently generates approximately 250 new products each year.

The European food packaging market is valued at £2.4 billion a year of which Pactiv currently has a 2-3 % share. A further 60% is accessible; leaving 57% market share that Pactiv could exploit. This is potentially a very exciting market to be in.

Pactiv currently has the best product range on the market and is viewed by customers and competitors alike, as a "sleeping giant".

4.2 Move Towards Enhanced Environmental Performance

Pactiv is trying to anticipate what it sees as major lifestyle changes. Public awareness of environmental damage and the amount of packaging ending up as litter is causing concern. New forms of packaging are being developed to tackle the ever-increasing waste management problem. Meanwhile, Pactiv is developing and delivering innovative speciality packaging solutions to meet the market requirements.

The company faces some major environmental concerns:

a. How to reduce the environmental impact from Pactiv's current production
b. What will be the impact of the development and use of biodegradable packaging materials?
c. How compostable are the biodegradable alternatives lauded as suitable for home composting?
d. What is the true environmental performance of biodegradable alternatives in comparison with traditional polymer packaging? A life cycle assessment is needed.

This research project was initiated in response to pressures from the UK government to reduce the amount of waste and to address the demands of the EU packaging directive. Both of these require that Pactiv rethink their materials strategy.
Various opportunities were identified, in particular sustainable biodegradable materials, which are less open to attack from pressure groups such as Green Peace on environmental grounds. Green Peace has been campaigning against the use of chlorine for many years now and their hit list includes: PVC (Polyvinyl Chloride), PS (Polystyrene), PET (Polyethylene terephthalate and finally Polyolefins such as PP (Polypropylene), LDPE (Low Density Polyethylene) and HDPE (High Density

Polyethylene). All of these are used by the packaging industry and by Pactiv. Green Peace prefers biodegradable polymers (from sustainable resources), but ultimately they would like reusable packaging or no packaging at all, neither of which are currently viable options in today's market.

Pressures such as these have affected Pactiv's big customers. Marks and Spencer for example made it publicly known that they wanted to stop using PVC packaging by the end of 2002. Pactiv therefore have a vested interested in making biodegradable polymers commercially viable.

The identification of low cost materials from sustainable resources, which could be easily processed and would meet current food packaging requirements, was key to the research.

Biodegradable materials need to be either cost competitive with current materials or meet the needs of growth markets such as the organic market that would be prepared to pay the extra cost of environmentally friendly packaging. By contrast, various studies [2][3] have shown that oil-based packaging materials (all of which Greenpeace are campaigning against) are in fact economically efficient. This is due to high production rates, which reduce manufacturing time and lower the overall requirement for energy. Oil-based packaging is also environmentally efficient due to low material usage in production, for example, when thermoforming light-weight packaging. The life cycle assessment carried out confirms that oil-based plastics are more environmentally sustainable than biodegradable plastics.

Investigations carried into Pactiv's 3 main manufacturing sites in the UK have shown that there is scope to reduce oil-based material waste going to landfill. Therefore, in conjunction with research into biodegradable materials, current manufacturing processes and materials were investigated with a view to making them more efficient, minimising cost and reducing the requirements for materials manufactured from non-renewable resources.

4.3 Pactiv's Manufacturing Process

Pactiv has a two-stage manufacturing process: firstly sheet extrusion and secondly thermoforming of food packaging containers.

4.3.1 Sheet Extrusion

Extrusion is a method that has been well-established for many years in polymer and food industries. It is used to form extrudates with defined cross-sections such as sheets and objects as diverse as spaghetti and fettuccini through to garden hosing. Various materials can be extruded including aluminium, clay rubbers, some foods and of course plastics.

Initially polymer in pellet form (Figure 4.12) is fed into the extrusion hopper. The pellets drop into a heated barrel and are conveyed and kneaded by a screw until they form a homogenous molten state, referred to as "the melt".

Figure 4.12: Thermoplastic in a pellet format

The melt is extruded at the end of the barrel through a shaping die as a continuous line of shaped plastic. This line is then pulled or hauled off through rollers (Figure 4.13) where it solidifies and is cut to length or coiled.

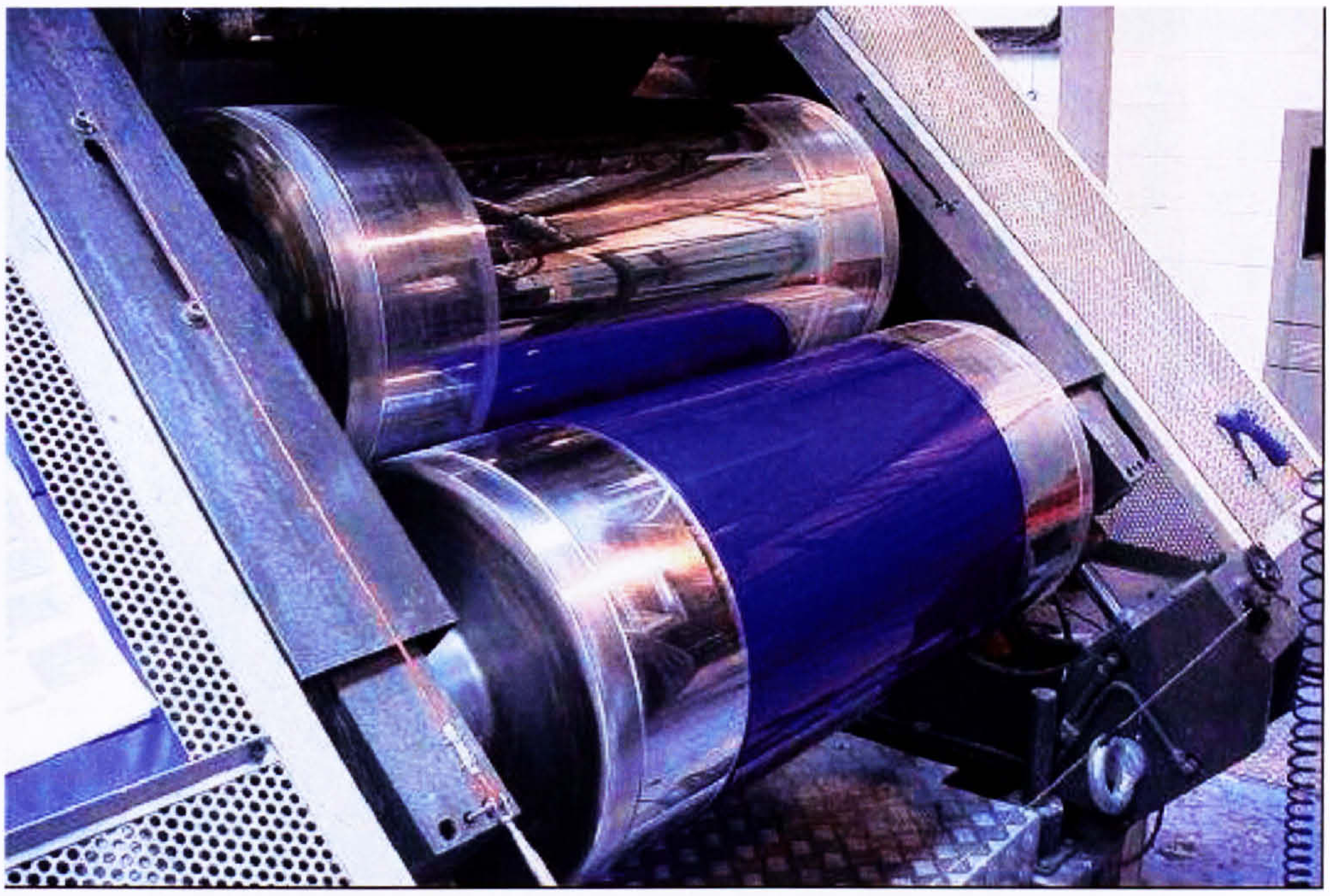


Figure 4.13: Plastic being hauled off through rollers

In Pactiv's case, they use a process known as sheet extrusion where thermoplastic resins, normally in pellet form, are transformed into a roll or sheet through a combination of heat and pressure as shown in figure 4.14.

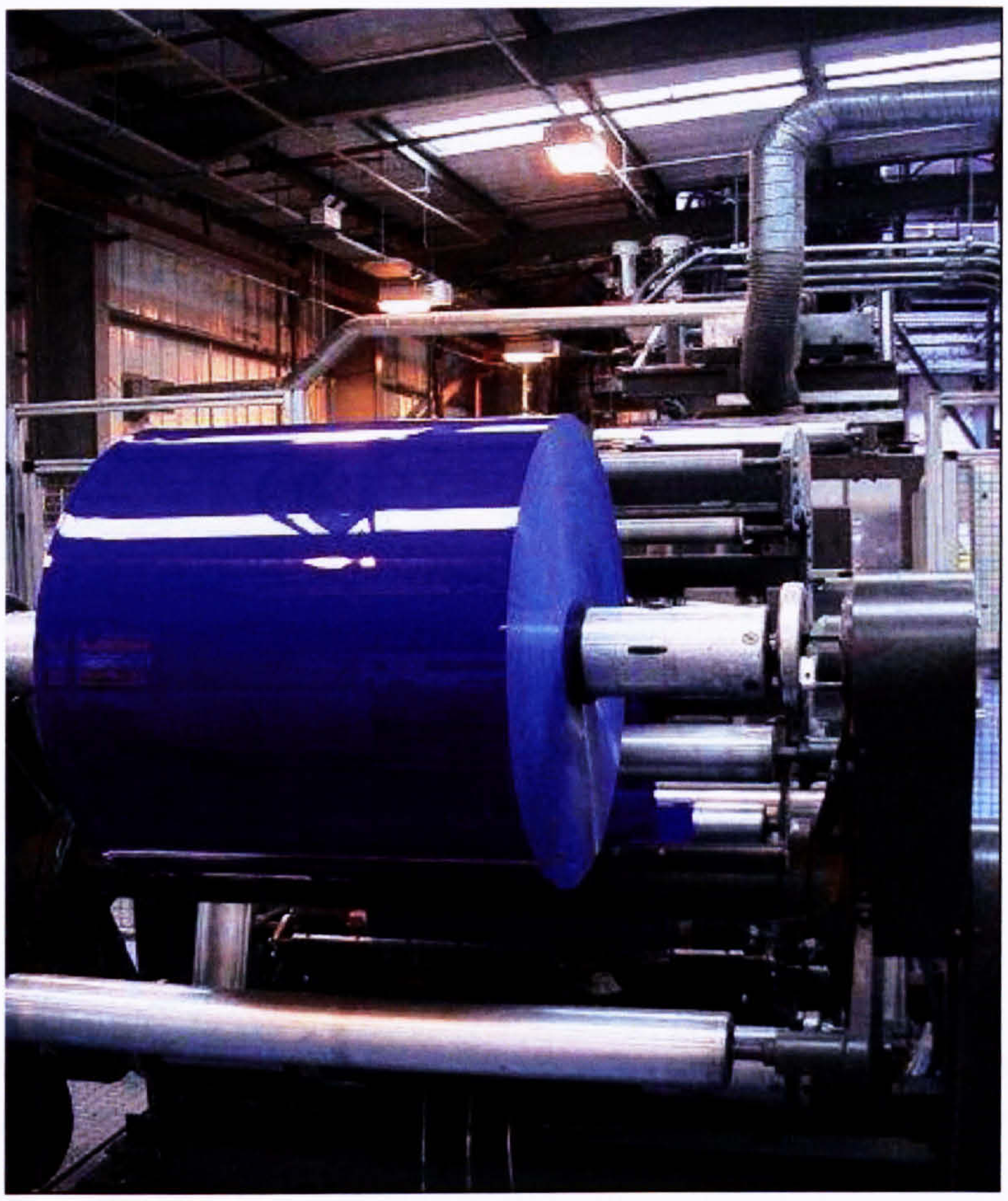


Figure 4.14: Thermoplastic resin transformed into sheet

The sheet is then formed in-house, into various shapes using a thermoforming process (Figure 4.15). The remaining sheet, which has not been thermoformed into product, is known as skeletal waste and is wound into a bail as shown in Figure 4.15.

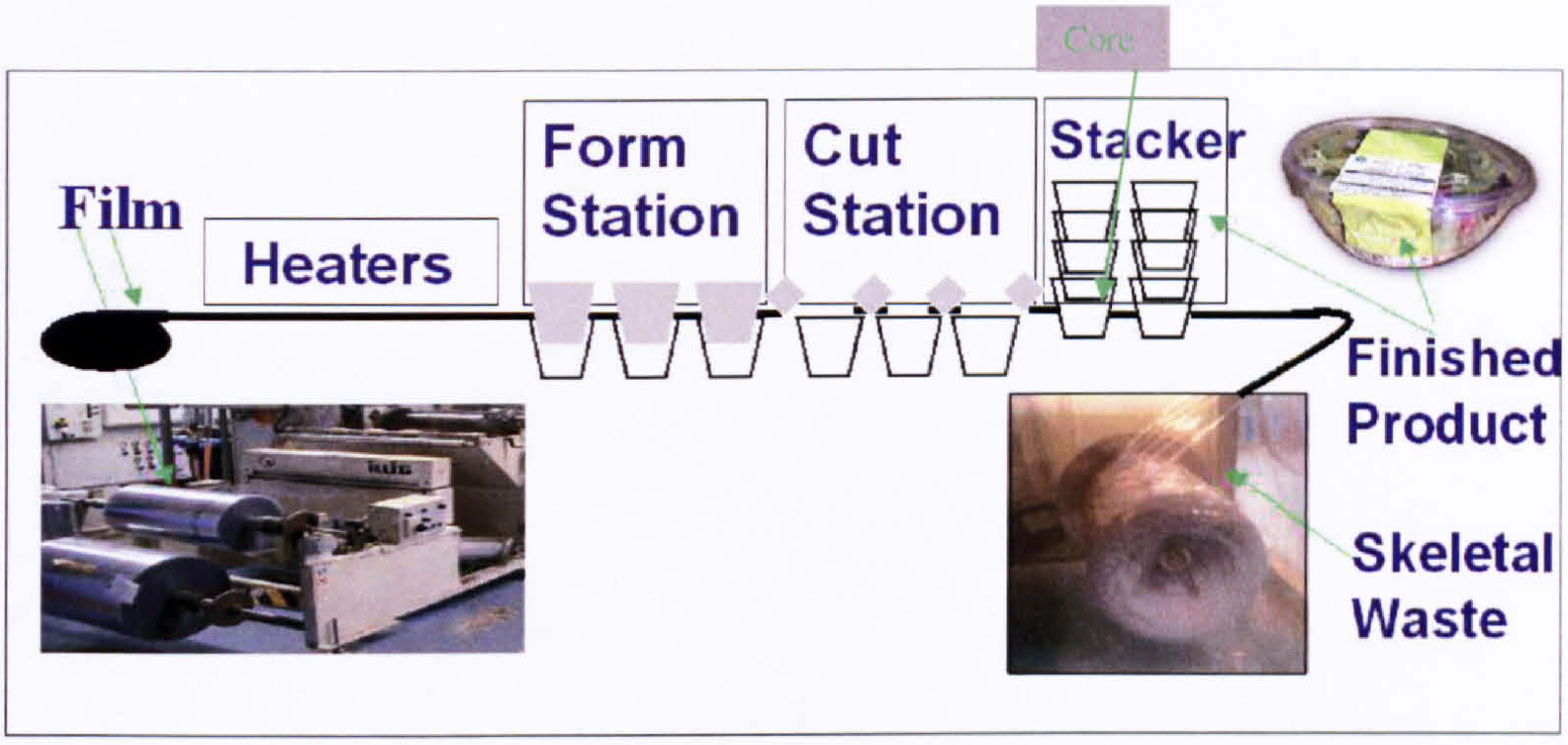


Figure 4.15: Thermoforming Schematic

There are three primary techniques used to manufacture thermoplastic sheet:

1. Extrusion through a flat die onto casting rolls
2. Extrusion through an annular die onto a sizing mandrel. The pipe like cross section that is extruded is slit in one or more places and then flattened and handled as sheet
3. Resins and additives are plasticated between large rolls and then sized through a series of additional rolls into a flat sheet. This process is known as calendering.

Each of these methods has advantages and disadvantages depending on factors such as the type of polymer being processed, the thickness and width of the sheet and the surface quality desired. As sheet extrusion is the primary technique adopted at Pactiv, it will be referred to in the remaining sections unless specified otherwise.

4.3.1.1 Single layer flat extrusion

Single layer flat sheet extrusion is the most common technique used in extruding plastic sheet for the thermoforming industry. The classic procedures for this process can be described as follows:

- Resin is fed into an extruder where it is plasticated into a melt
- The extruder consists of a heated barrel with an internal rotating screw, which pumps the melted resin through a flat sheet die that defines the sheet size (thickness and width)
- The sheet exits the die in a semi-viscous state and travels through a series of rolls to cool. These rolls determine final sheet thickness, width and surface finish
    - The flat sheet is then wound onto continuous rolls into discrete lengths

4.3.1.2 Co-extrusion

Co-extrusion is a process that allows the combination of different materials and/or colours in a single sheet in a laminated form. This is used to achieve special required properties (such as barrier properties), for aesthetic effects with colour, or for economic reasons where an inexpensive material substrate is combined with a more expensive material 'cap'.

4.3.2 Thermoforming

The process of thermoforming dates back to the Romans, who imported tortoise shell (Keratin) from the Orient to shape into food utensils using hot oils [4]. More recently vacuum forming was used to make items such as aircraft canopies, turrets and domes during World War II. After this period, thermoforming rapidly grew into a practical and profitable method of processing plastics. Today, thermoforming is quite possibly the fastest growing method of processing plastics.

Thermoforming is a generic term for the process of producing thin-shelled plastic parts from a flat sheet under elevated temperature and pressure. Thermoforming offers high production rate, close tolerances, tight specifications and sharp detail. When combined with advanced finishing techniques, high technology thermoforming results in products comparable to those formed by injection moulding. For these reasons, thermoformed plastics have replaced many parts previously manufactured from wood, paper, glass and metal.

A production process will only be successful if the articles it manufactures can be produced more cost effectively than by an alternative process, or if it can produce articles of a higher quality for a similar cost. There are areas of application where injection moulding or blow moulding compete with thermoforming for complex bulk structure or for thin films. In the packaging industry, however, thermoforming generally only has products from cardboard and paper to compete with.

The most advantageous aspects of thermoforming are its high output rate, low tooling and engineering costs and its fast turnaround time. These advantages make thermoforming ideal for prototype development and low volume production. Uses of thermoformed plastic products include automotive interiors, shipping and packaging containers. Initial project costs are usually much lower and lead times to tooling and production are generally much shorter than other processes. Temporary tooling offers an inexpensive short-term test for sorting out design issues and product market acceptance. Thin-walled articles can be produced from forming material of high melt viscosity, whereas with the injection moulding process, such mouldings require granulate material of low melt viscosity. With a small number of mouldings, the favourable tool costs offer yet another advantage to thermoforming; with large batches, the benefits of thermoforming are to be found in the very low wall thickness' achievable and the high output rate of thermoforming machines.

Thermoforming involves seven fundamental processes:

1. Using resin to form sheet, or film material
2. Heating the sheet
3. Using a vacuum and compressed air to form the product
4. Heating the mould to a desired temperature
5. Cooling the part
6. Cutting and trimming
7. Stacking and packing

There are two main methods of thermoforming: *vacuum forming* (Figure 4.16) and *plug-assisted pressure forming* (Figure 4.17).

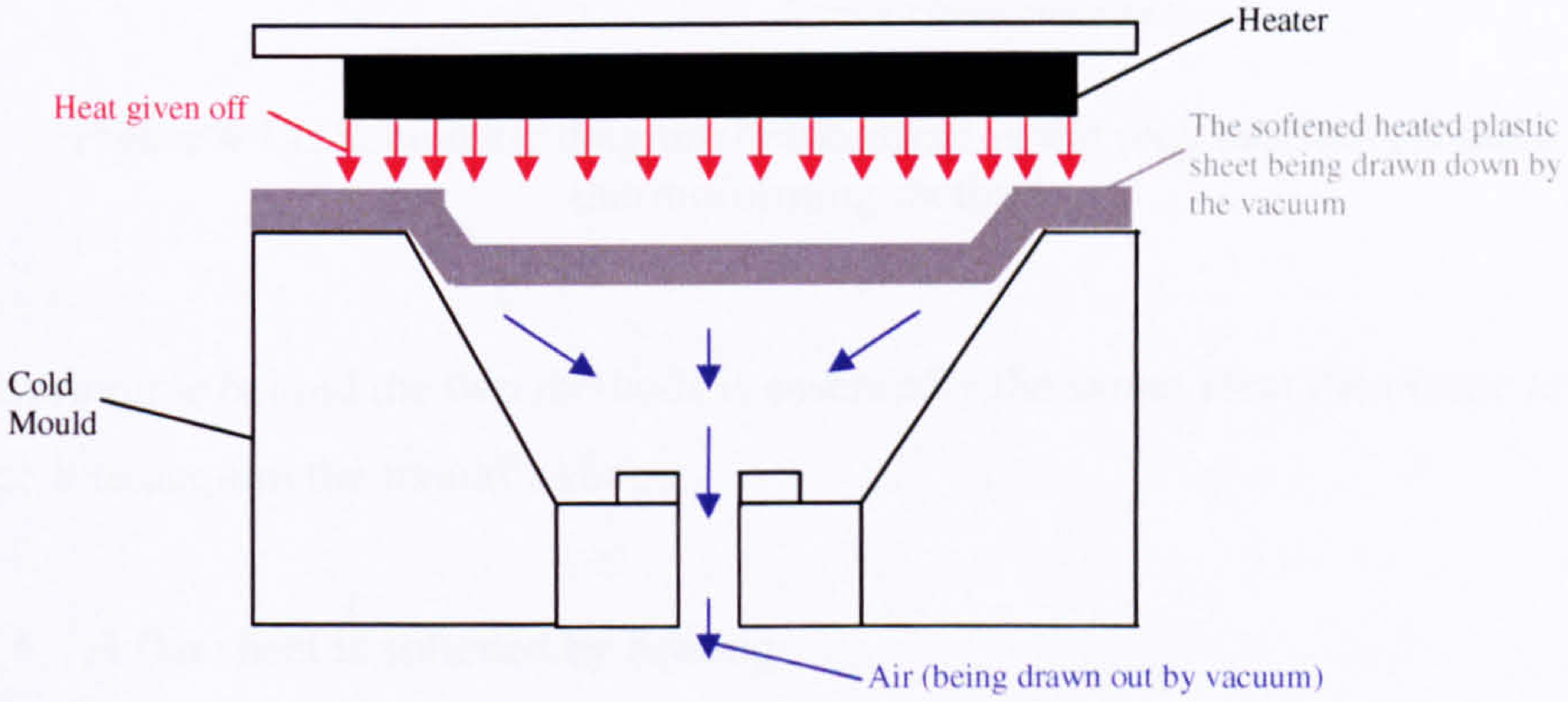


Figure 4.16: Schematic diagram showing a Vacuum Thermoforming Method

In vacuum forming:

- A flat plastic sheet is softened by heating
- The softened sheet is placed over a chilled mould
- A vacuum draws the sheet into the cavity within the cold mould
- The part is removed and cut or trimmed

Plug-assisted pressure forming, Pactiv's chosen method of thermoforming, uses compressed air and mechanical pressure:

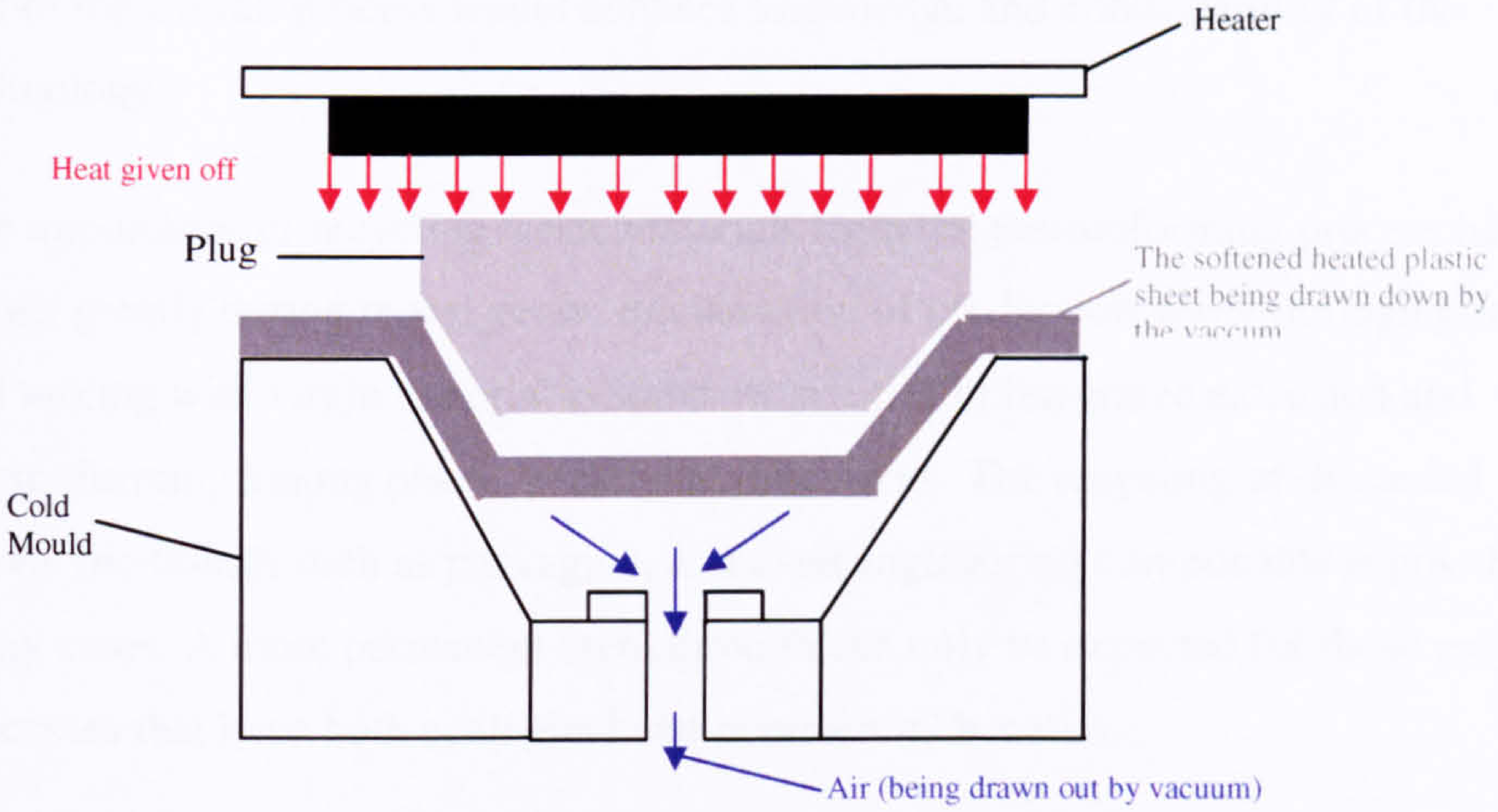


Figure 4.17: Schematic diagram demonstrating the plug assisted pressure thermoforming method.

The principle behind the two methods is essentially the same: Heat the plastic and force it to acquire the mould's shape:

- A flat sheet is softened by heating
- The sheet is placed over a mould cavity.
- The plug mechanically stretches the sheet into the cavity.
- This is accompanied by applying a positive over pressure (approx 5 bar) and vacuum (approx 1 bar)
- The plastic hardens on contact with the cold mould surface.
- The part is removed and subsequently cut/ trimmed from the web.

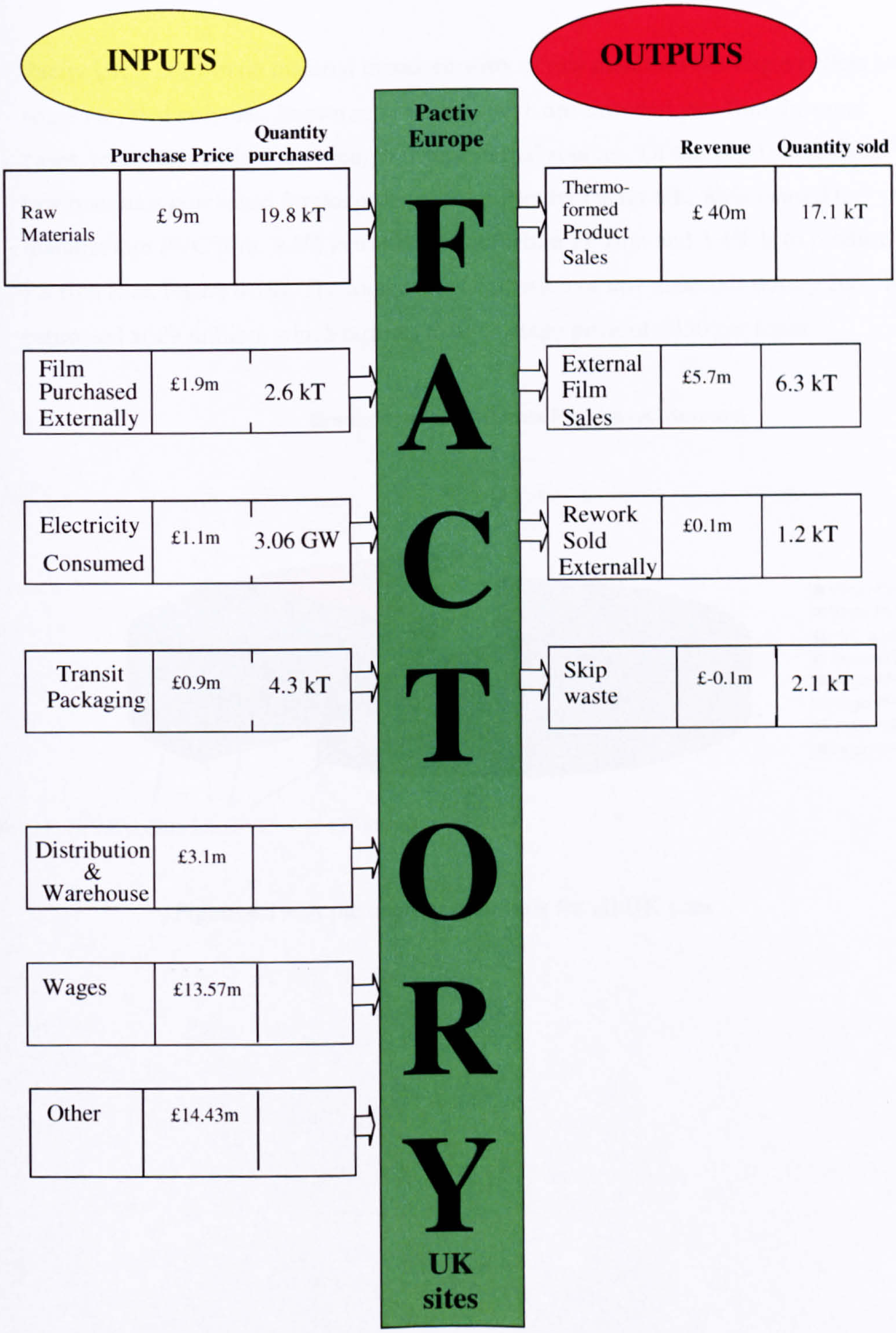
Within plastics processing, thermoforming is regarded as the area with the highest growth potential. This applies to technical mouldings as much as to plastics packaging. [4]. At present thermoforming is still largely a process relying on high levels of craftsmanship and experience. As such, simulations of materials behaviour and of the overall process would enhance knowledge and controllability of the technology.

The importance of recycling waste materials from the thermoforming process has grown greatly during recent years. Reclamation of production waste through grinding and mixing with virgin material is standard practice in integrated extrusion and thermoforming among plastic packaging processors. The recycling of discarded plastic mouldings such as packaging, and even engineering components is possible in many cases. A more permanent breakthrough can only be expected for those recycling processes that have both ecological and commercial benefits.

4.4 Overview of Pactiv UK's Inputs and Outputs

In order to determine Pactiv's areas of financial concern with an environmental impact, Pactiv's financial accounts were examined and the data collated into a diagram (Figure 4.18) that highlights areas of environmental concern along with their associated costs. Cost is an important issue as any process modifications must incur a cost saving as well as an environmental improvement if they are to achieve buy-in from the business.

4.4.1 Pactiv UK's 2001 Materials Inputs and Outputs



INPUTS	Purchase Price	Quantity purchased
Raw Materials	£ 9m	19.8 kT
Film Purchased Externally	£1.9m	2.6 kT
Electricity Consumed	£1.1m	3.06 GW
Transit Packaging	£0.9m	4.3 kT
Distribution & Warehouse	£3.1m	
Wages	£13.57m	
Other	£14.43m	

OUTPUTS	Revenue	Quantity sold
Thermo-formed Product Sales	£ 40m	17.1 kT
External Film Sales	£5.7m	6.3 kT
Rework Sold Externally	£0.1m	1.2 kT
Skip waste	£-0.1m	2.1 kT

Figure 4.18: Pactiv UK's 2001 Inputs and Outputs

4.4.2 Pactiv UK's 2001 Material Inputs

Pactiv UK's 2001 main material inputs consists of raw materials (as virgin pellets and some recycled polymer, known as rework), which are extruded into film. In some cases, ready-made films are brought from external sources. Of the 19,819 tonnes of raw materials purchased for the production of film by Pactiv UK, 88% is used to manufacture PVC film. 8.6% is used to manufacture PP film and 3.4% is to produce PS film (See Figure 4.19). The total cost of extrusion of raw materials during 2001 is estimated at £9 million, which equates to an average price of £450 per tonne.

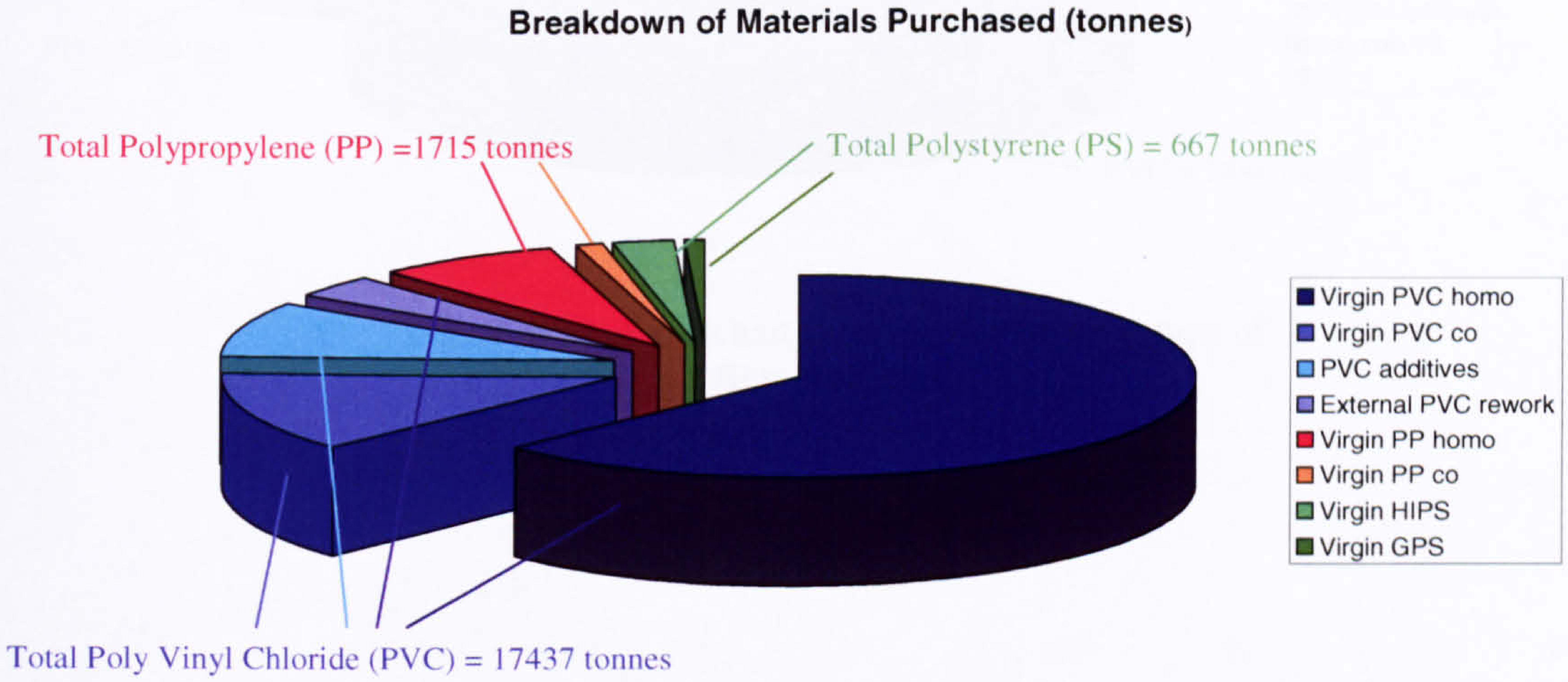


Figure 4.19: A pie chart of materials for all UK sites

Of the 2,635 tonnes of film purchased externally, 70 % was PVC. A further 12.6% was PE for the manufacture of PVC / PE laminate. The remaining 9.8% was APET (Figure 4.20).

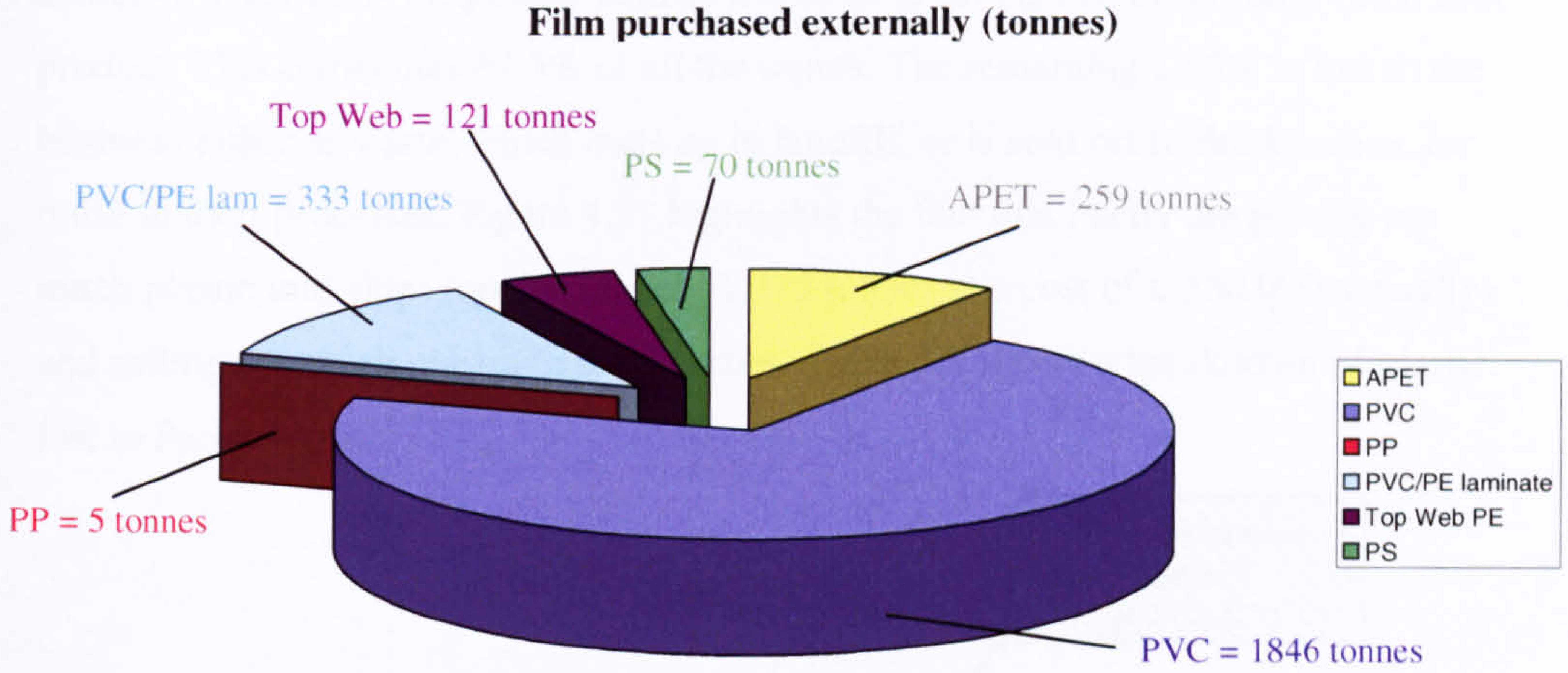
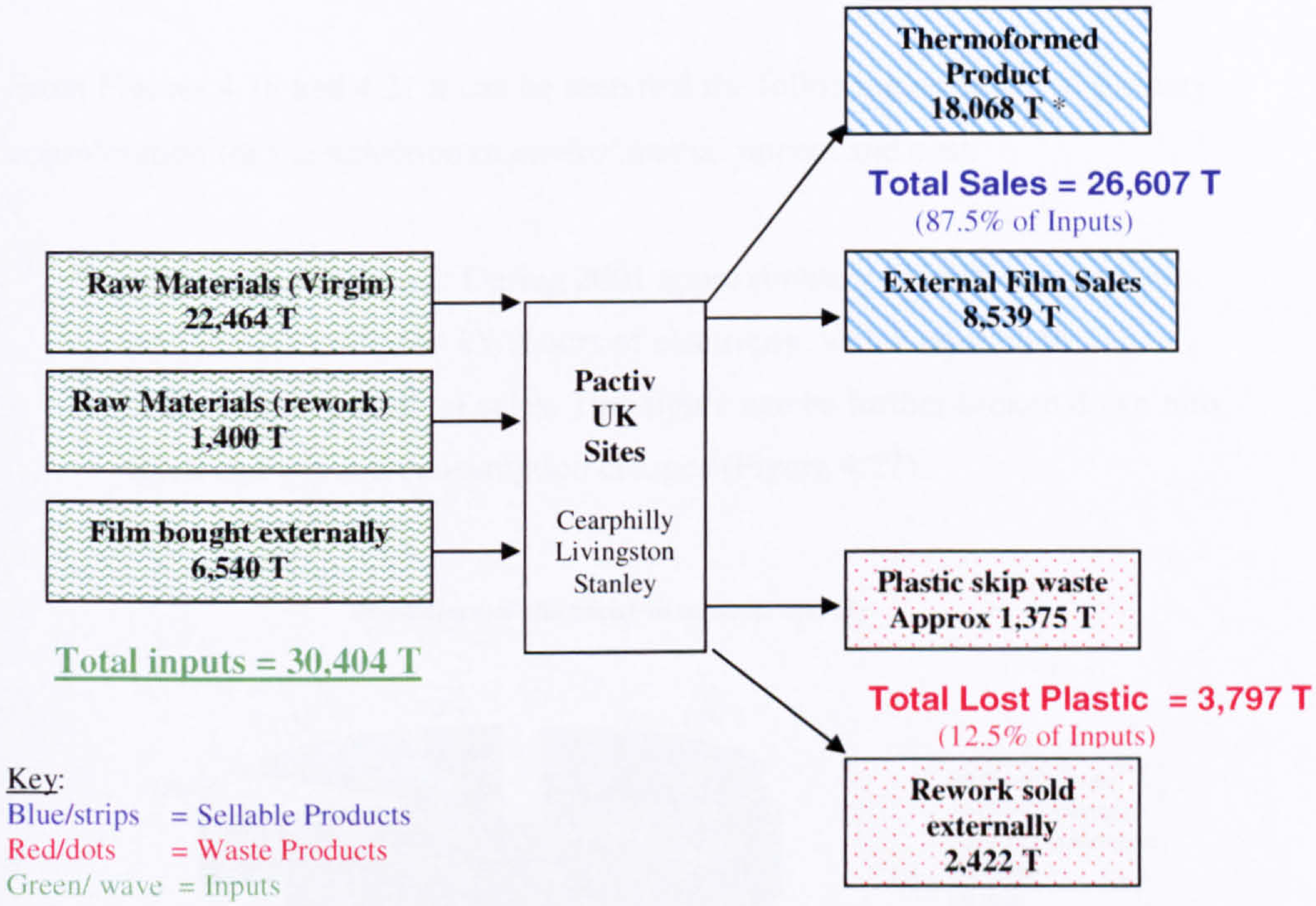


Figure 4.20: A pie chart showing the material type of film purchased

4.4.3 Pactiv UK's 2002 Inputs and Outputs Summary

In 2002, as in 2001, the main material inputs consist of raw materials - both virgin and rework - which are extruded into film (In some cases film is bought from external sources). The film is then either sold as it is to external clients, or thermoformed into product. This constitutes 87.5% of all the inputs. The remaining 12.5% is lost to the business either as waste, which ends up in landfill, or is sold off to third parties, for reuse in their processes. Figure 4.21 highlights the fact that Pactiv are putting too much plastic into skips (approximately 1,375 tonnes at a cost of £ 550,000 annually) and selling too much plastic to third parties. Table 4.2 shows a breakdown of plastic lost to Pactiv by site.



* Thermoformed Product Total weight calculated from Total inputs – (Total Lost Plastic + External Film Sales)

Figure 4.21: Basic Inputs & Outputs of Pactiv UK's three Thermoforming / Extrusion sites in 2002 [1]

Table 4.2: Breakdown of plastic lost to Pactiv UK's in 2002 [1]

Year 2002	*Stanley (tonnes)*	*Livingston (tonnes)*	*Caerphilly (tonnes)*	*Pactiv UK Total (tonnes)*
Rework sold externally	272	800	1,350	2,422
Estimated plastic in skips	600	410	365	1,375
Total plastic lost to Pactiv UK	**872**	**1,210**	**1,715**	**3,797**

4.5 Analysis of Pactiv's 'Hot Spots' of Environmental Concern

From Figures 4.18 and 4.21 it can be seen that the following areas are of primary consideration for the reduction of environmental impact and cost:

- Electricity consumed: During 2001 approximately £1 million was spent providing 30,603,444 kW/hours of electricity, which equates to approximately 2.5% of sales. This figure can be further broken down into fixed charges and consumption charges (Figure 4.22).

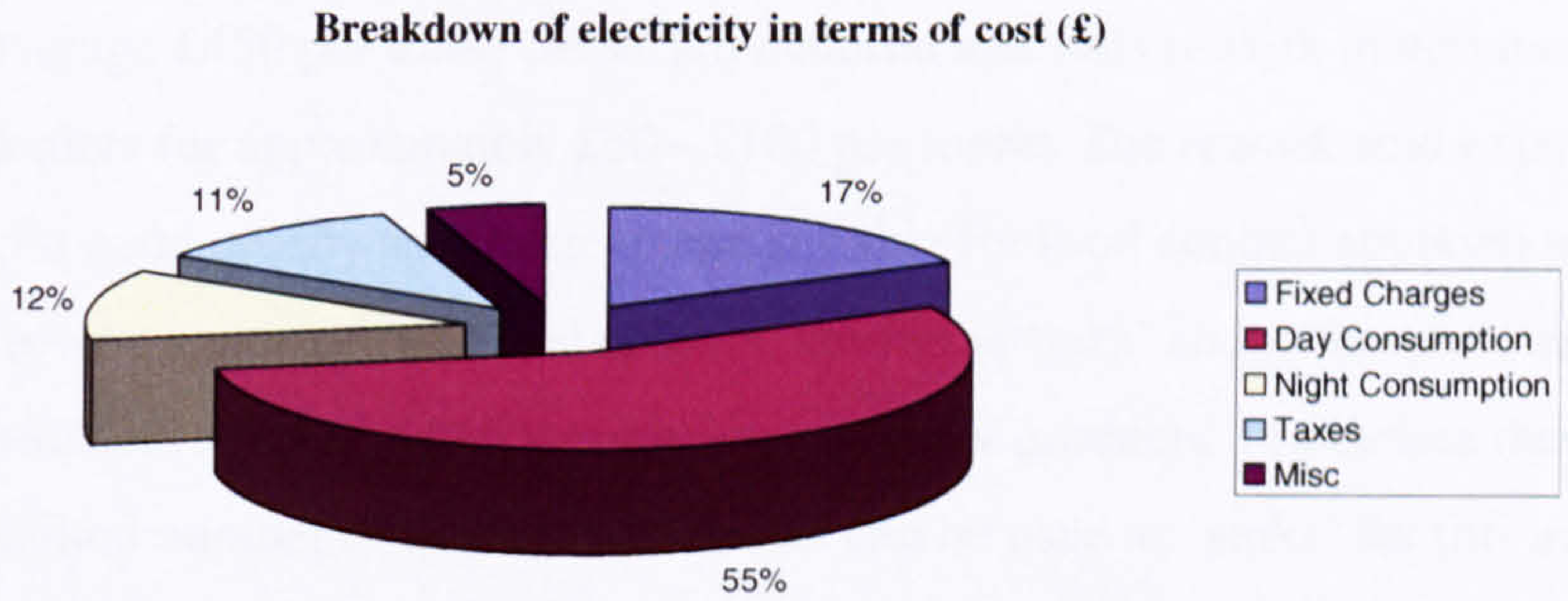


Figure 4.22: Breakdown of fixed and per- consumption electricity costs (£)

The processes and practices of the company are to be investigated with a view to reducing the electricity consumed. This will be a financial as well as an environmental benefit.

Extensive research has previously been carried out into electricity usage at the Caerphilly site of the company. This will be reviewed in the project and used to enforce the analysis of inputs and outputs.

- Transit Packaging: The data collected showed that £900,000 per year is currently spent on 4,341 tonnes of transit packaging, which constitutes approximately 16% of the total materials input (in terms of weight). The transit packaging can be further broken down in terms of materials as shown in Figure 4.23.

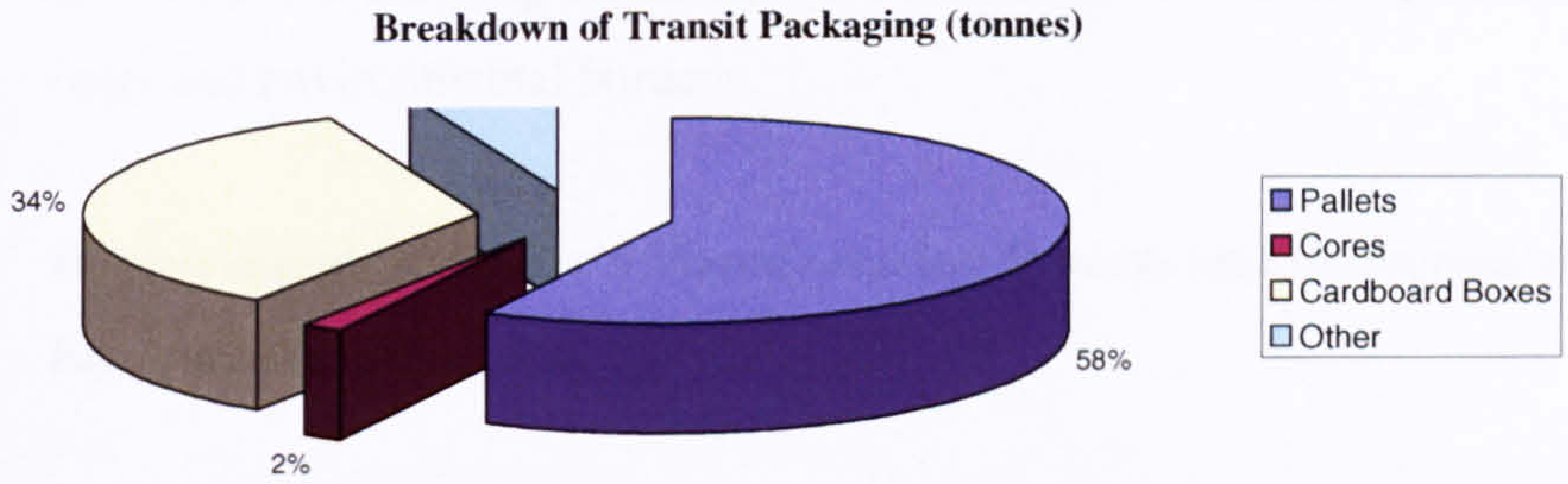


Figure 4.23: Breakdown of transit packaging materials by weight per year over across all Pactiv UK sites

- Rework sold externally: This refers to material that is sold to scrap dealers for a small percentage of its original purchase price. For example, Pactiv pays on average £450 per tonne for virgin material and sells rework material to scrap dealers for approximately £50 - £100 per tonne. The rework sold externally is of a good quality as it is clean and suitable for food contact applications. However, it is often mixed colours, known as 'jazz' and is therefore only suitable for reuse when thermoforming black products. In practice there are a limited number of black products that can be used as 'sinks' for this material. In 2001, 1,200 tonnes of rework material were sold to scrap dealers for a total of £100,000, resulting in a loss of £440,000, which equates to 6% of all raw materials inputs.

This is an area that has a major impact on the material efficiency and costs of the business. Therefore this part of the project aims to reduce the lost revenue, primarily by reducing the amount of rework material being sold and by increasing the price per tonne of the clean rework.

- Plastics sent to landfill: In 2001 Pactiv UK produced a total of 2,100 tonnes of skip waste material that was sent to landfill of which 1,000 tonnes were estimated to be wasted plastic.

Preliminary investigation has suggested that this estimate could be a very conservative one. The analysis of Pactiv's 'Hotspots' project primarily proposed to reduce the amount of material being sent to landfill. The project then looked at reducing the amount of collections, thus reducing transport costs and environmental burdens.

4.6 Improvements to Pactiv's Manufacturing Process and Reduction of its Environmental Burden.

Following the analysis of the "hot-spots", the following projects were identified based on their potential for commercial and environmental gains:

- Reduction of Reprocessing waste: How best to deal with Pactiv's waste streams and turn what is currently an expense into an economically viable and environmentally sound process
- Reduction of electricity consumption
- Reduction on tonnage of transit packaging used
- Reducing haulage to Pactiv's external warehouses

Some of the "hot-spot" projects were rejected by Pactiv's senior leadership team, only those that were accepted are discussed below.

4.6.1 Reduction of Reprocessing Waste

Pactiv UK is a typical food packaging company, and as such the problems it experiences with recycling are representative of the industry as a whole. During the first two years of the project, work has been carried out to reduce the amount of material Pactiv UK sends to landfill.

This process was investigated in detail in order to understand where Pactiv UK's environmental burden could be improved. The 2001 figures were collected and a basic block diagram of inputs and outputs was constructed as shown in Figure 4.18. Firstly, this highlighted some areas for improvement within the Pactiv process, notably the amount of clean, food-grade approved, reprocessed plastic known as rework, which has been sold off cheaply rather than replacing virgin material, which was worth £450 per tonne in 2001.

A second problem is the tonnage of waste going to landfill (Figure 4.24). A conservative estimate is that 1,000 of the 2,200 tonnes of waste sent to landfill was clean plastic (Figure 4.25). This plastic could instead be reprocessed into rework, which in turn could be used in place of the virgin polymers.

Figure 4.24: An example of general waste that goes into Pactiv's compactor bins

Figure 4.25: A close up of the general waste showing skeletal waste and reject forming

The cost analysis behind this statement is as follows:

- 1,200 tonnes of rework sold off cheaply to third parties generated a revenue of £100,000
- 1,000 tonnes of clean plastic sent to landfill cost Pactiv approx £ 50,000

Assuming that 100% of the 2,200 tonnes above could be successfully used to replace the virgin polymers, worth £450 per tonne, the 1200 tonnes of rework would potentially be able to generate £940,000 per annum saving as shown below:

2,200 tonnes x £ 450 per tonne = £ 990,000
1,200 tonnes not sold off cheaply = £-100,000
Reduce 1000 tonnes of landfill costs = £ 50,000
Total cost saving = £940,000

Therefore this project could potentially save Pactiv £940,000 per year, whilst significantly reducing its environmental impact by reducing the amount of plastic materials going to landfill.

Due to both economic and environmental reasons this skeletal waste material needs to be reduced in volume suitable for reprocessing and compacted into a denser format suitable for transportation. There are several methods of reducing skeletal waste into a useful format: bailing, shredding and granulating. All of these were investigated.

4.6.2 The Bailing Process

One method of reducing the size of the skeletal waste is to compress it. This can be done using a bailer. A mill size vertical bailer GB500 from Green Bank in Leeds (UK) was used to bail Pactiv's skeletal waste and rejected trays in an experiment to ascertain whether bailing is a viable option for compression.

A GB 500 'mill size' vertical bailer (Figure 4.26) was used to bail 9 transport pallets of Polypropylene skeletal reels and additional reject trays.

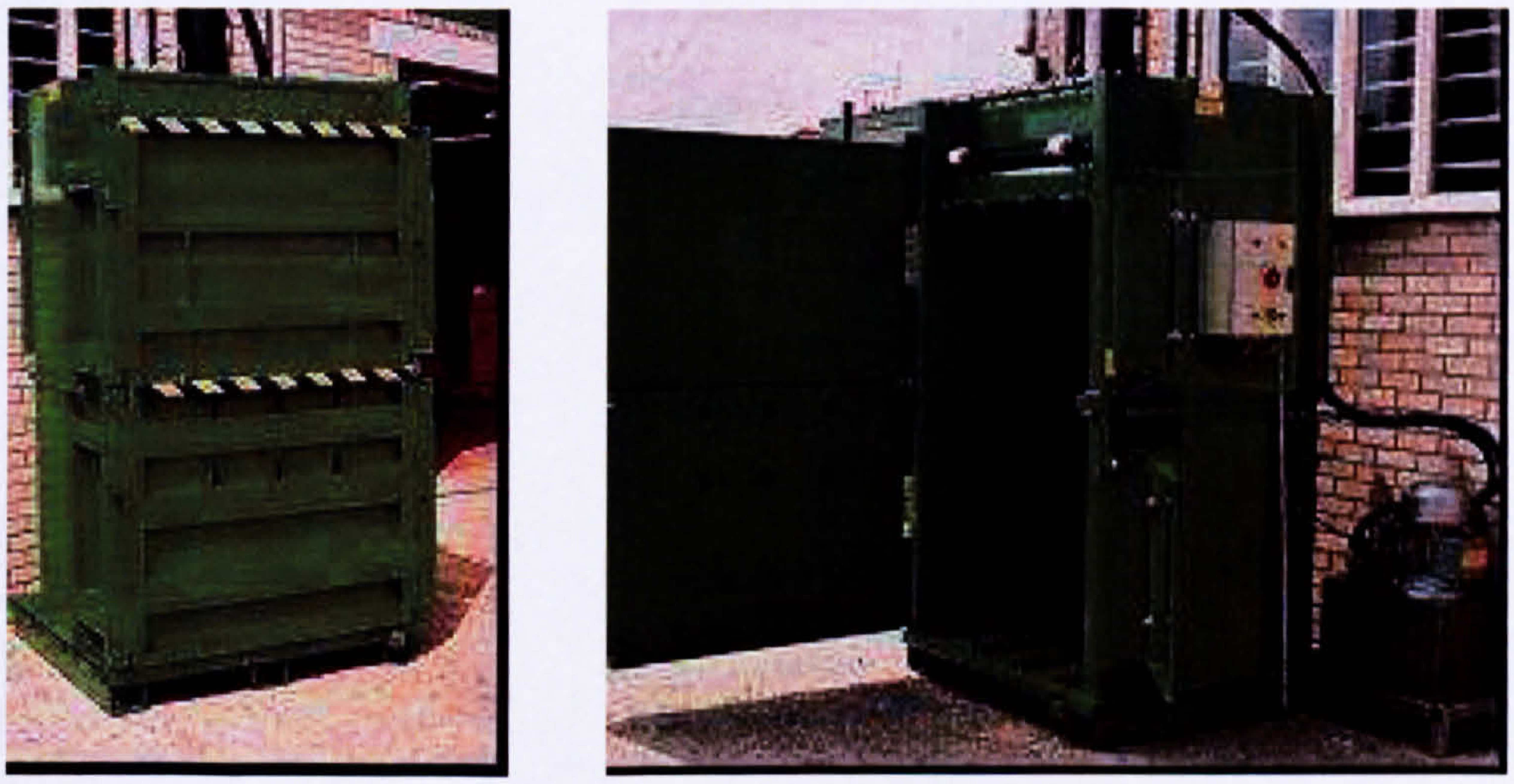


Figure 4.26: Green Bank's GB500 mill size vertical bailer used for this investigation

The machine was operated in accordance with instructions from Green Bank representatives. The bailer has two different setting:

- Card: Suitable for bailing used paper and cardboard
- Plastic: Suitable for bailing used lightweight plastic, such as plastic bags.

Both settings were investigated, as skeletal waste had not previously been compacted using such a bailer. There are also two methods for securing the bail: using a plastic tie, or using metal tie, both of these were also investigated. The time taken to complete a bail, the number of skeletal reels used, the pressure applied and the effect of adding reject trays on the bailing process were recorded. Figure 4.27 illustrates the bailing process at different stages:

Stage 1: Skeletal waste being loaded into the feed chamber of the baler
Stage 2: Result of first compression
Stage 3: Loading the skeletal waste for the 4th compaction – demonstrating manual operation necessary
Stage 4: A nearly full bail
Stage 5: Trial using a plastic tie
Stage 6: Trial using a metal tie
Stage 7: The bail can then be ejected onto a pallet if a standard fork lift is to be used
Stage 8: The resulting bail on a pallet

Stage 1

Stage 2

Stage 3

Stage 4

Stage 5

Stage 6

Stage 7

Stage 8

Figure 4.27: Procedures in the bailing process

Table 4.3 and 4.4 present two typical records of the bailing process.

Table 4.3: Results of a trial using card setting and plastic ties within a 30 minute bailing process

No. of Compactions	*No. of skeletal waste bales*	*Loose forming's included (y/n)*	*Pressure of compaction (bar)*
1	7	N	30
2	3	Y	30
3	2	N	30
4	2	Y	60
5	1	Y	60
6	3	N	90
7	0	N	Not recorded

Table 4.4: Results of a trial using plastic setting and plastic ties within a 30 minute bailing process

No. of Compactions	*No. of skeletal waste bales*	*Loose forming's included (y/n)*	*Pressure of compaction (bar)*
1	6	N	Not recorded
2	4	N	Not recorded
3	3	N	50
4	2	N	60
5	3	N	Not recorded
6	2	N	Not recorded
7	3	N	110
8	3	N	140
9	3	N	160
10	2	N	Not recorded

In conclusion, the experiment was a success. The Green Bank vertical bailer successfully bailed the skeletal waste and loose rejected containers. Nine transport pallets of skeletal reels were compressed into three experimental bails, which could be transported on 3 pallets. Loose rejected containers were successfully incorporated into the bails. The bailing process could therefore be used to compress Pactiv's plastic waste into a denser format suitable for transportation to other users, who do not require product to meet food hygiene standards. This replaces the need for virgin material to be used in less critical applications. The process was, however, very labour intensive and the resultant format of the material would only be suitable for other plastic processors if the bails were kept to one material type. This would require Pactiv keeping material types separate in holding bays until sufficient quantity had been collected to make a bail. It was decided that this would require too much man-power and space and would detract from Pactiv's main manufacturing focus. Therefore, other options were considered.

4.6.3 The Shredding process

Another method of reducing the volume of the scrap material is to shred the skeletal waste plastic material and loose reject formings using a shredder. The main advantage of this method is that skeletal waste reduces in size far more quickly than with a bailer or a granulator (Pactiv's current method for reducing the volume of their scrap material). Also, a shredder can be used in conjunction with Pactiv's in-house rework, further speeding up the process. Another advantage is that a shredder can be cleared much more quickly than a granulator, should the type of material need to be changed. One disadvantage, however, is the initial expense of the machine. An Untha LRK 1000 shredder (Figure 4.28) was borrowed from Plastic Process Polymers, who currently process some of Pactiv's granulated jazz (mixed coloured rework) to shred Pactiv's skeletal waste and reject trays and ascertain whether shredding would be a viable process. After shredding the material can either be placed into bulk bags for sale, rather than being placed into the skip and landfilled or can be reprocessed by Pactiv, replacing the need for virgin polymer.

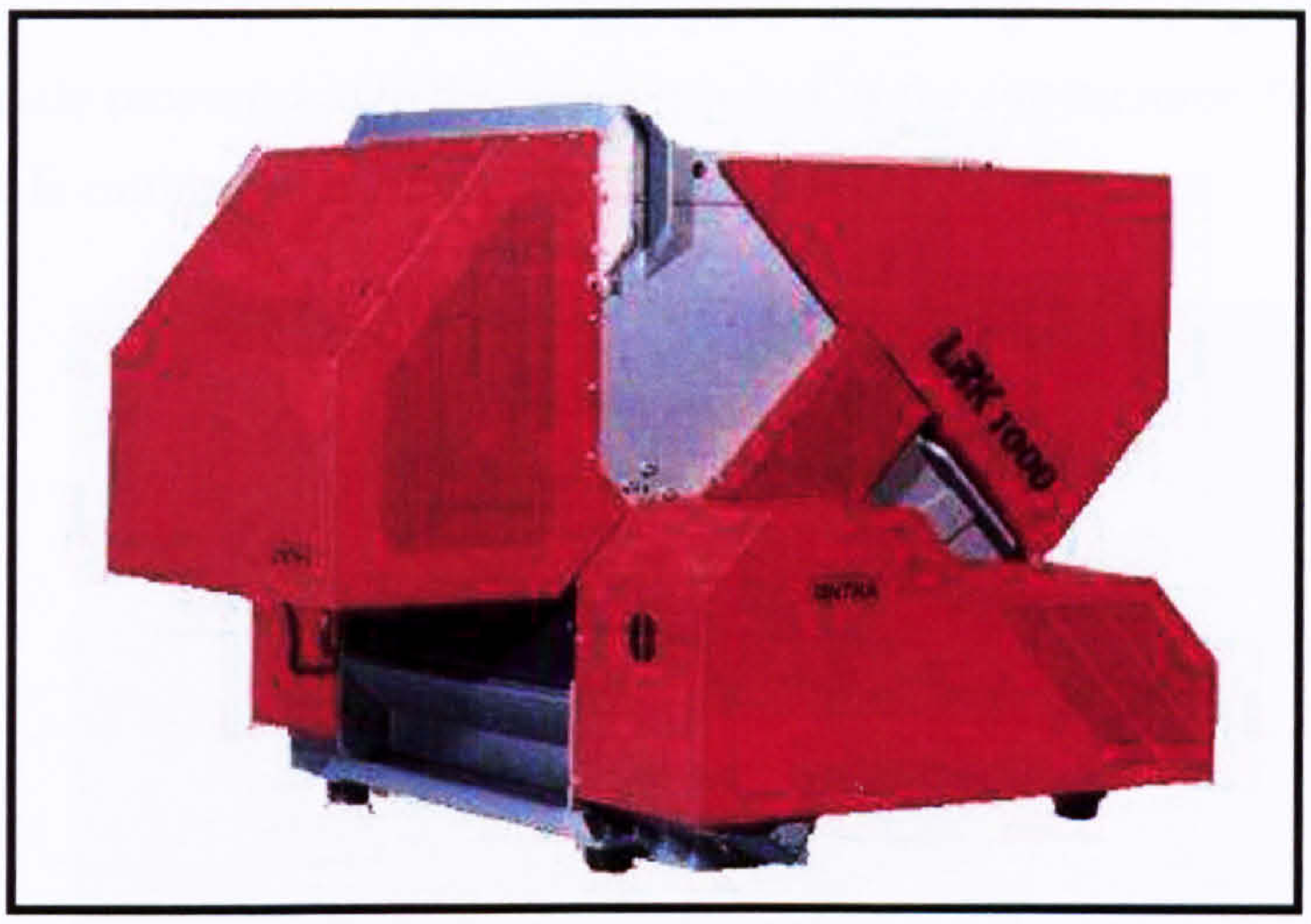


Figure 4.28: The Untha LRK 1000 Shredder used for this investigation.

The shredder was used to shred polypropylene and APET skeletal reels. The machine was operated in accordance with instructions from representatives of Plastic Polymer Processors representatives. The material was placed in the hopper as shown in Figure 4.29.

Figure 4.29: Skeletal waste plastic material being manually placed into the hopper

A hydraulic ram then pushes the material against the cutting rotor (Figure 4.30) with a force inversely proportional to the power required by the cutting rotor, fitted with exchangeable cutting plates (Figure 4.31).

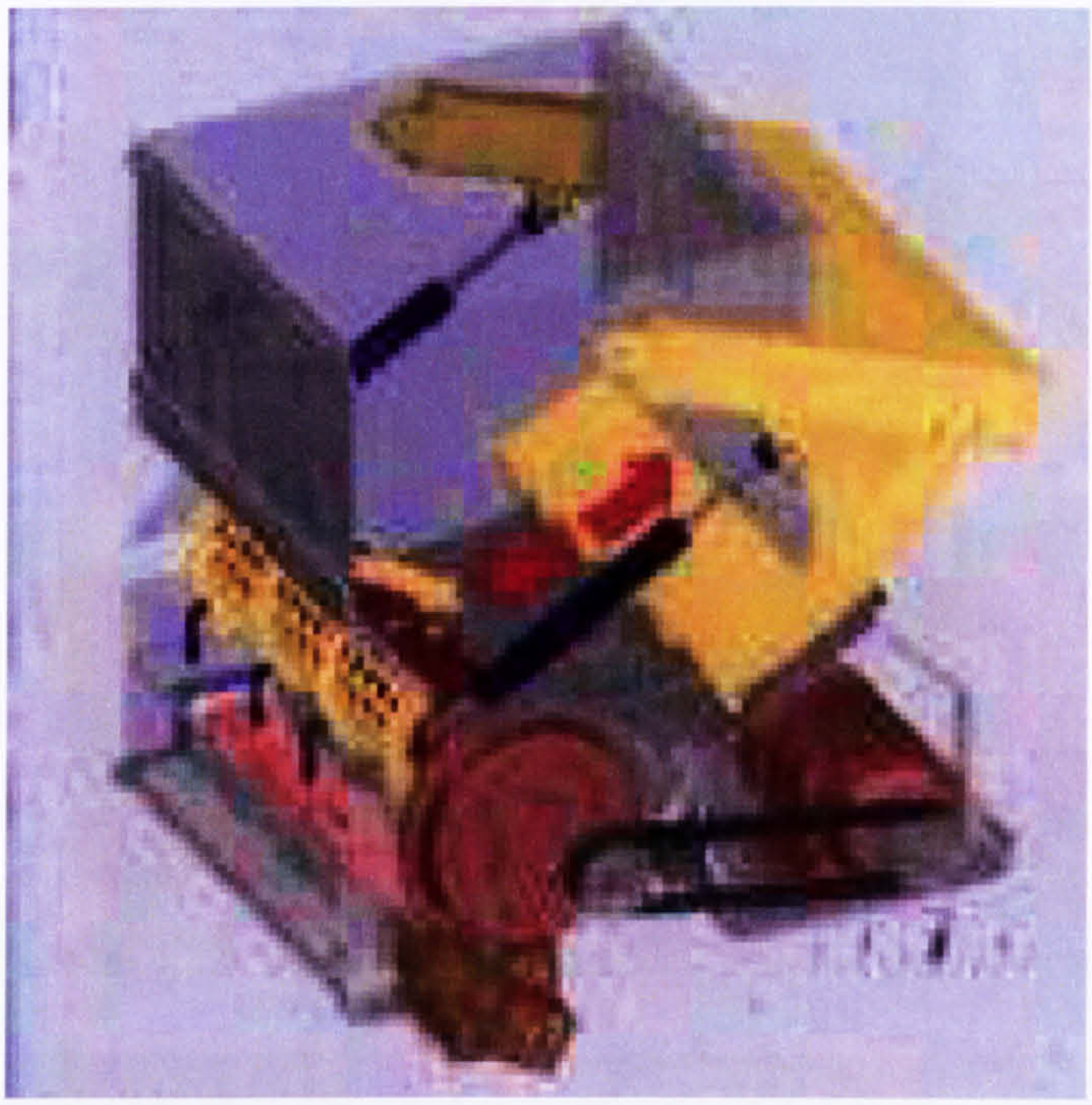


Figure 4.30: A schematic diagram of the shredder demonstrating the action of the hydraulic ram

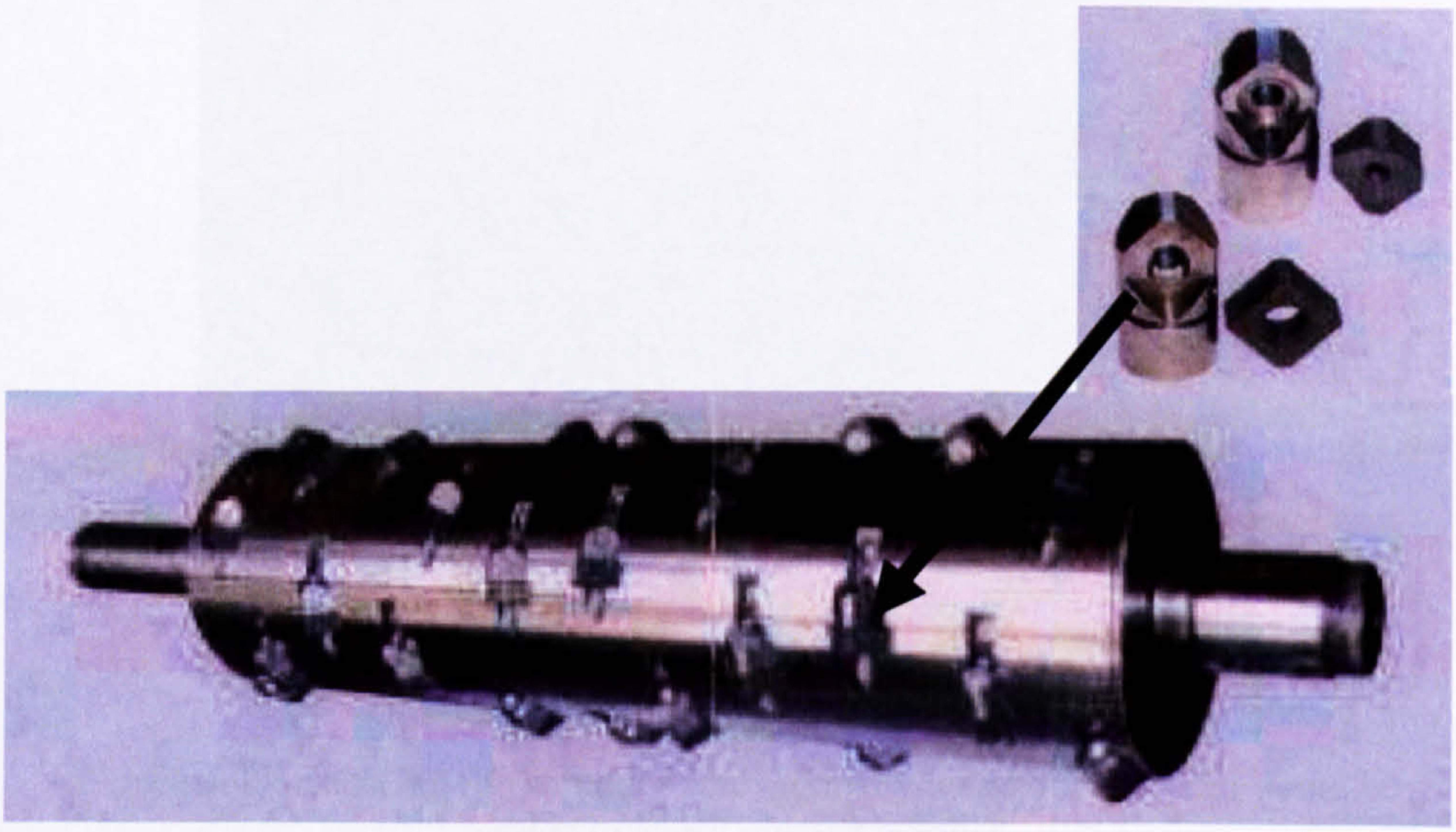


Figure 4.31: The shredder rotor blade and detailed image of the cutters

The cut materials then fall through a screen with a predefined mesh size (Figure 4.32) before being transported out of the shredder by means of a screw conveyor (Figure 4.33).

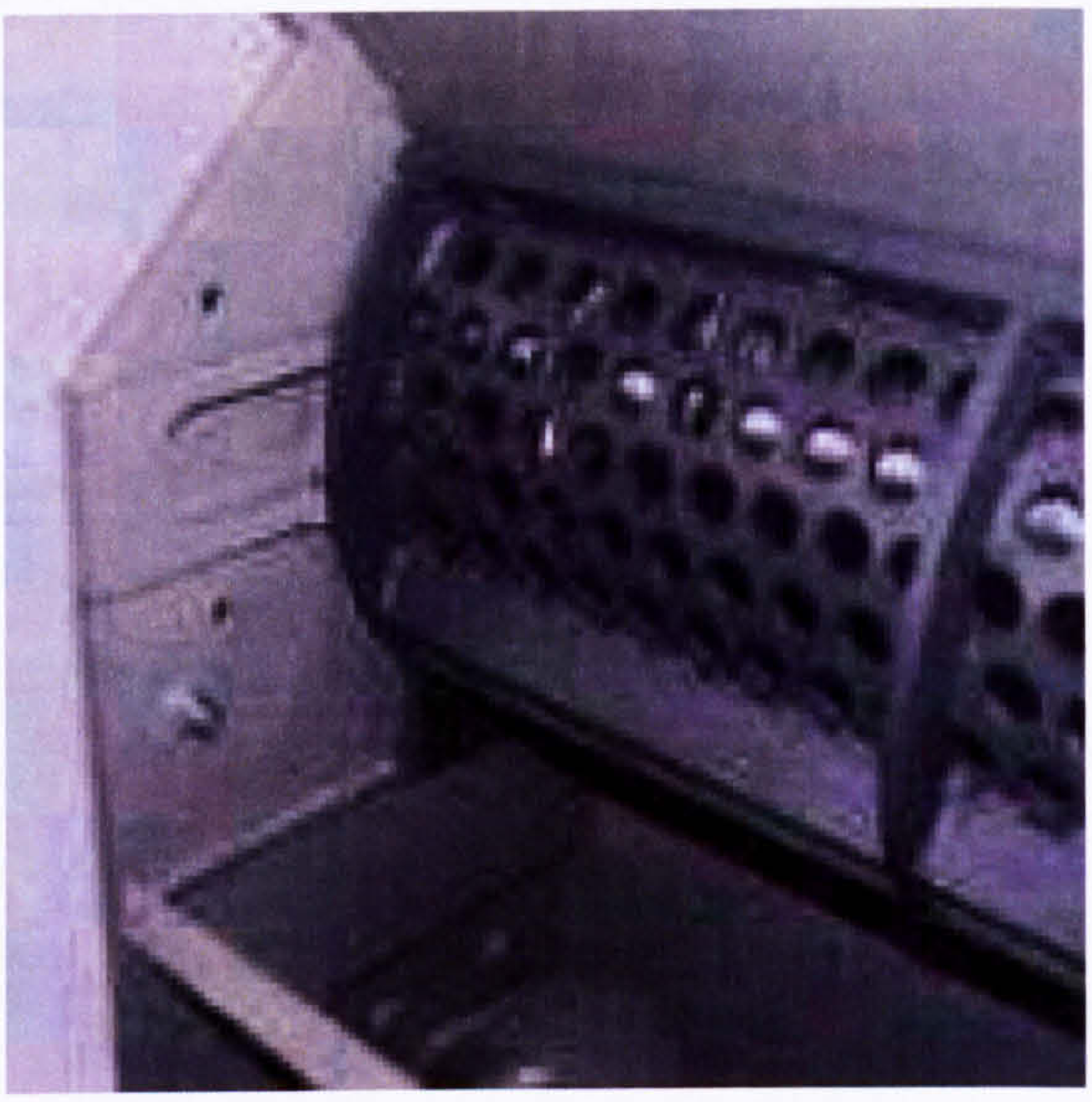


Figure 4.32: The screen that shredded material passes through

Figure 4.33: Showing the shredder screw conveyor (a hopper loader could be added to avoid manual labour)

The average size of the flakes produced is determined by the selected size of the screen hole diameters. The LRK shredders have a pivoting ram which allows the machine to be compact whilst ensuring a steady feed to the cutting mechanism. A spring tensioned belt drive system is used to drive the machine, which absorbs shocks during the shredding process. The forward pushing movement of the ram is directly dependent on the power required. A Siemens SPS controls the shredder and there are a number of safety measures in place:

- An automatic reverse prevents the motors for overloading
- An automatic damage protection shut down protects the cutting mechanism from potentially destructive objects or materials
- An automatic shut down that would kick in should the shredder runs idle for more than the preset time

The time taken to shred one skeletal bail (approx 300kg) of APET was 2 minutes. This equates to 2.5kg/hr. It was noted that shredded material was of an increased temperature relative to the input material, which would potentially cause problems if the shredded material were to be granulated immediately. A suggested solution to this problem would be to increase the screw length, thus allowing the material to cool. Polypropylene skeletal bail, being a weaker material, was found to shred in a similar time, without any problems with temperature Therefore, this material has the potential to be granulated immediately.

The process was a continual process once loaded, and as such did not need human supervision. In the trial, small plastic boxes were used to collect the shredded material; however, there is the potential to use a conveying system (for example a vacuum hopper loader). Overall, the experiment was a success. The Untha LRK 1000 shredder was proved to be a suitable method for reducing the volume of the skeletal reels quickly, with minimal labour and is suitable for reprocessing Pactiv's rework.

4.6.4 The Granulation Process

Pactiv's current method of reducing their scrap material into a useful format is granulation, which is very similar to shredding. Granulation is the preferred method for Pactiv as no additional capital expenditure is required and the resultant regrind is suitable for reprocessing. An example of Pactiv's granulation process is shown in Figure 4.34. A case study was carried out with a view to highlight potential areas of improvement to both the process and the machinery.

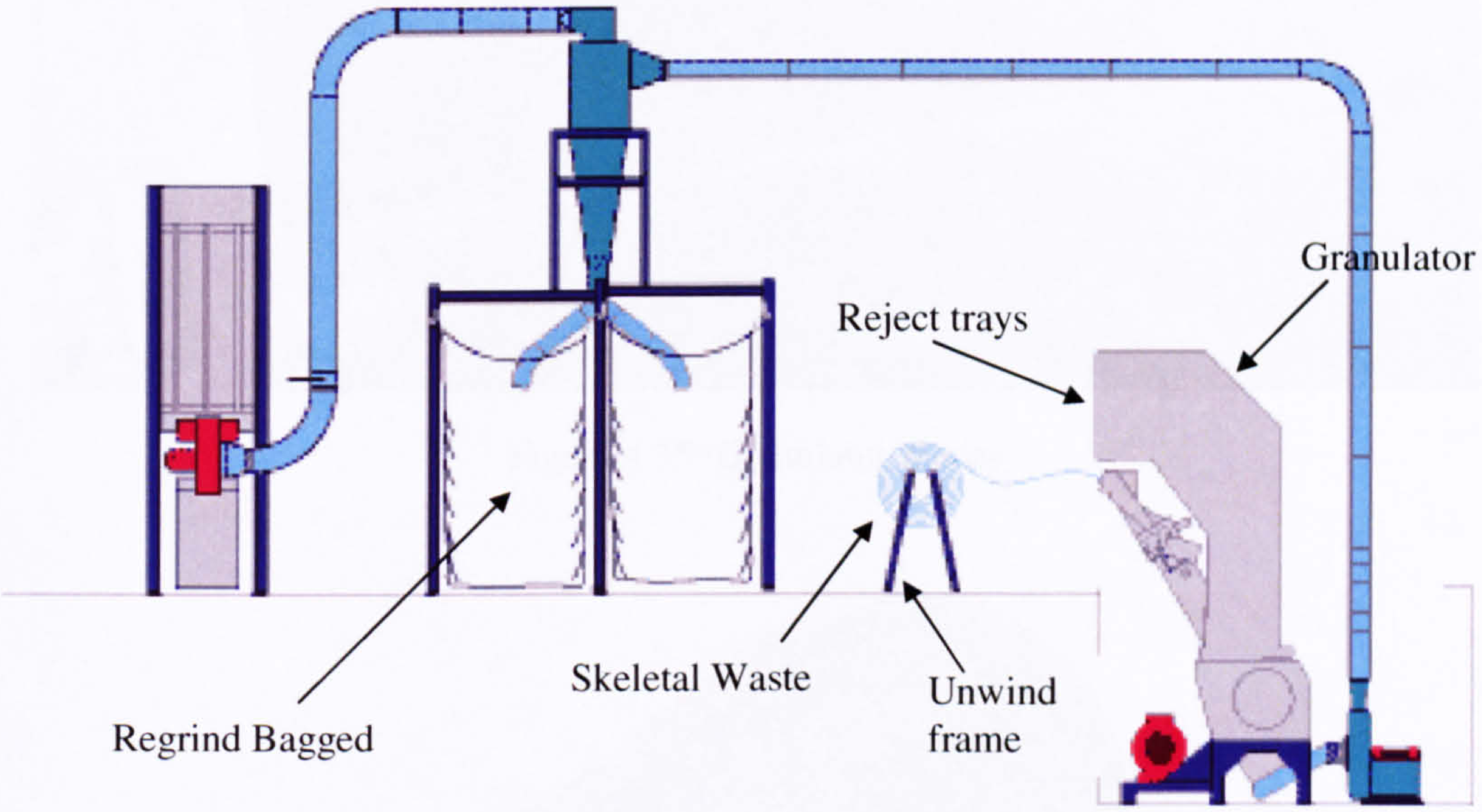


Figure 4.34: Diagram of Pactiv's granulation process

Plastic scrap comes in varying formats. In Pactiv's case it is predominantly skeletal waste, the film remaining after the product has been formed. Pactiv's other scrap is rejected trays, which are all different sizes and shapes. Before this plastic waste can be extruded into plastic sheet and subsequently thermoformed into new products, it must be reduced in size. The skeletal waste is loaded onto an unwind frame (Figure 4.34) and feed into the granulator. The granulator blades (Figure 4.35) reduce the plastic in size until it fits through the mesh (Figure 4.36). The resultant regrind is then conveyed into bags (Figure 4.34) for storage and/ or transportation.

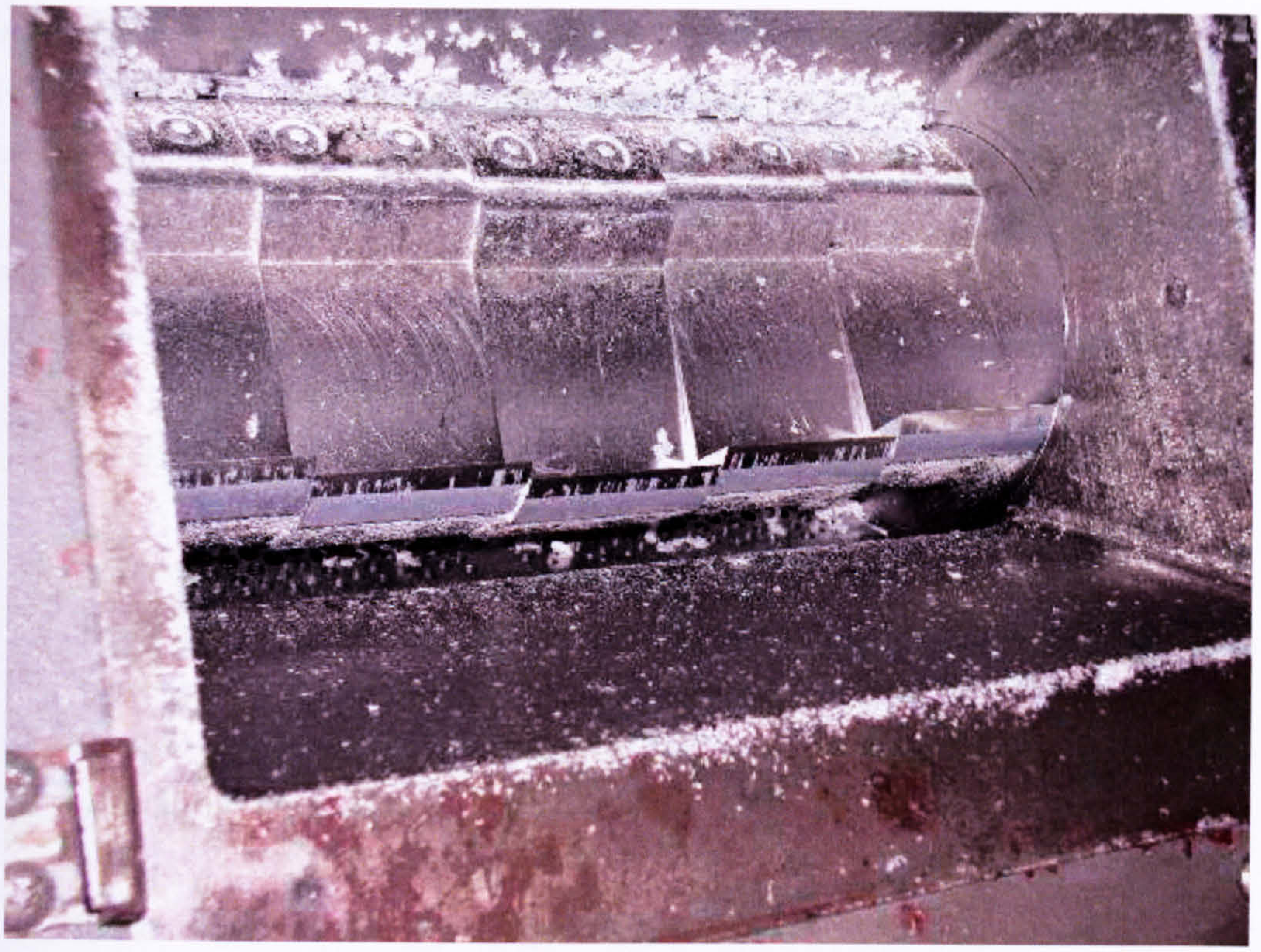


Figure 4.35: Granulator blades

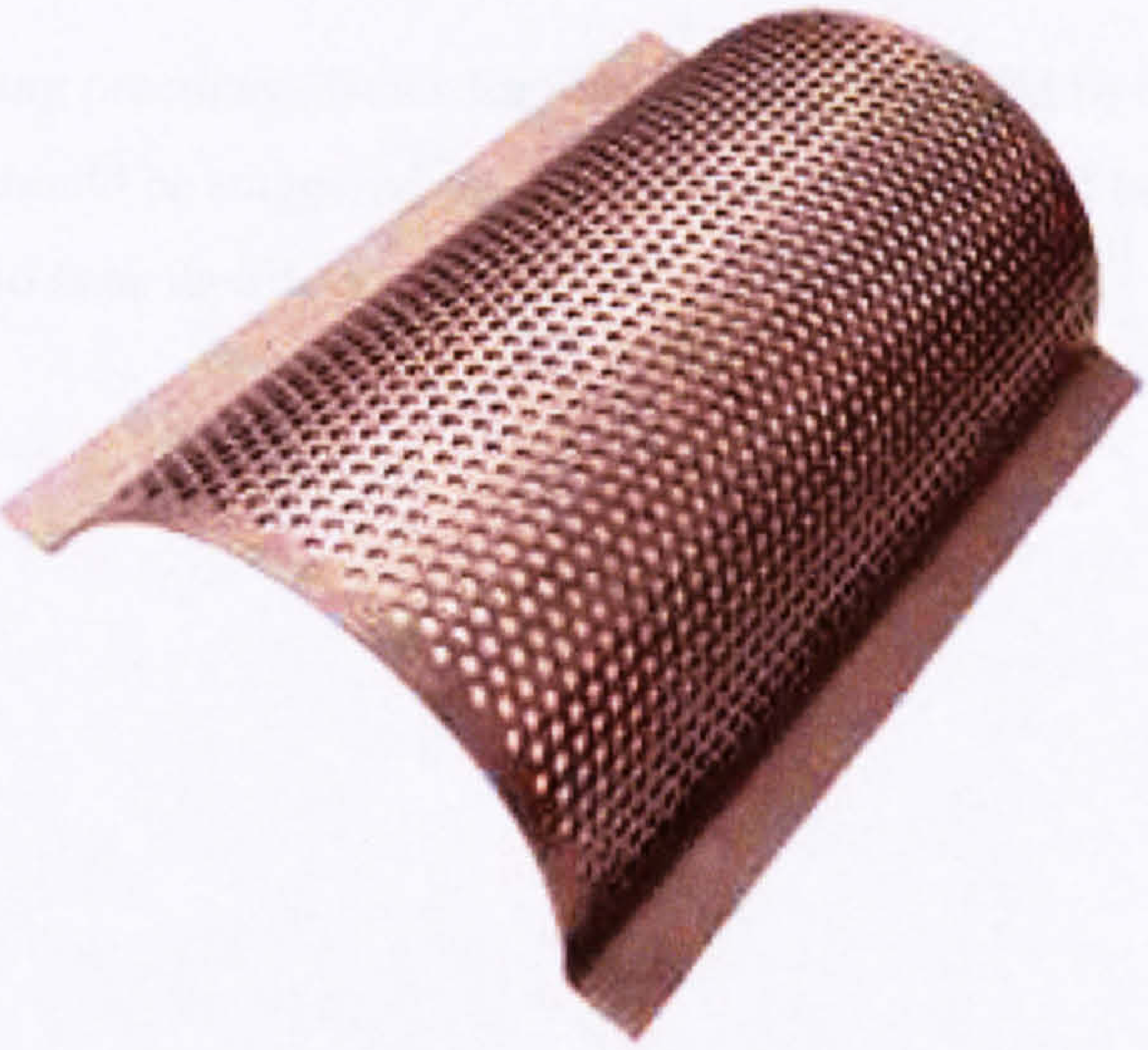


Figure 4.36: Granulator screen

Granulation is probably the most common form of plastic recycling. The process involves a set of rotating blades and often a fixed blade, which is used to chop the material. A screen is used to control the size of the resultant regrind.

Some potential improvements to the process were highlighted:

- Improving the identification of material types: All skeletal waste must be clearly labelled

- Reducing the time taken to change bags: It took the operators between 15 and 40 minutes to change a bag. A suggested improvement would be to get the new bag and pallet ready prior to the old bag being full. Once the bag has been changed granulation should recommence before weighing, wrapping and labelling the full bag

- Introduction of a holding grid: Operators were focused on keeping up with the material coming off the shop floor and were not granulating material from other sources such as reject rollstock and formings

- Smarter working practices: Times for operator breaks should be enforced, and these breaks should be staggered. Also a location board should be introduced for operators to state their location

4.6.5 Key Performance Indicators for Waste Reduction

The waste minimisation projects proved successful and were incorporated as a significant number of additional key performance indicators (KPI's), as shown in Table 4.5 (indicators 3 to8). These are used to keep track of improvements, waste reduction and to prevent projects slipping back into bad practices.

Table 4.5 An Example of Pactiv UK's Key Performance Indicators

2003 Key Performance Indicators	*Stanley Wk 15*	*Stanley Wk 31*
1. Tonnage Thermoformed	158	254
2. Tonnage Extruded	58	89
3. Tonnage Skipped	27	18
4. Tonnage of Rework sold to 3rd Parties	0	0
5. Tonnage of Plastic Lost to Pactiv	17	8
6. Tonnage Granulated	37	105
7. Tonnage of Rework Used	26	35
8. Percentage (%) Rework Used	44	40

KPi figures from week 15 and week 31 at the Stanley site (Table 4.4) highlight the improvements that have been made over the sixteen-week period. For example, thermoformed and extruded output tonnage has increased by 127 tonnes (63%), the amount of material skipped has decreased by 9 tonnes (67%) and the tonnage of plastic lost to Pactiv has decreased by 9 tonnes (47%). However these figures also show that the percentage of rework used has reduced by 4% from 44% to 40%. This information demonstrates where further improvements are necessary.

4.6.6 Reduction in the Cores used, Transit Packaging

Cores are transit packaging. The plastic sheet material is wound around them when being hauled off the extruder. Cores are used for transportation purposes and their role is to prevent the rolled plastic sheet collapsing. Two materials are currently being used, plastic and cardboard. The Livingston site uses only plastic, the Caerphilly site only cardboard and the Stanley site uses both plastic and cardboard cores. Whilst collecting this data suppliers were asked for figures and tonnages of all cores bought during the 2001 period. The objective of this project was to study the feasibility of manufacturing from Pactiv's rework.

The project was set up with a plastic core company using Pactiv's non-food grade PP rework plastic to make cores with potential cost benefits, whilst further reducing the amount of material being sent to landfill. Pactiv's Livingston site set up a core reuse procedure to determine how many times the plastic cores can be reused. Reuse has significant cost and environmental benefits as fewer cores would be purchased.

It was found that cardboard cores, which are significantly cheaper than plastic, could be successfully reused. Therefore a procedure of recycling cardboard cores for internal use has been implemented. Spend on cores has been significantly reduced from £33,000 in 2001 to £6,600 in 2003.

Unfortunately the attempt to manufacture plastic cores from Pactiv's rework was not successful as the core company proved that Pactiv's non-food grade rework was not of a suitable quality.

Further work investigated of the effects of reducing the wall thickness of the cardboard cores used for supplying external customers, as there is little scope for reusing these cores. A reduction in wall thickness could potentially reduce cost and material used, which currently ends up in landfill. Other ideas include investigating the feasibility of using technology that does not require the use of cores.

4.7 Summary

The changes implemented as a result of the work carried out by the Research Engineer were a resounding success and provided Pactiv Europe with short-term solutions to improve on its environmental footprint, whilst entailing the significant cost savings required to ensure its continued competitiveness and market positioning. Simply by changing working practices and increasing staff awareness of the importance of focussing on recycling and correctly segregating waste materials for re-work or re-processing, significant improvements were achieved.

By increasing the proportion of rework used, the amount of virgin material required and the volume of waste plastic was substantially reduced. This was achieved by improving material identification, improving the segregation of waste materials, improving storage facilities and practices and by employing more recycling equipment and operators. Furthermore, new revenue streams were found by reprocessing materials that did not meet food hygiene standards and selling them for lower grade applications rather than sending them to landfill. In short, by implementing measures to tackle the environmental impact of its production process, Pactiv also achieved a direct positive impact to its cost structure and working practices. If similar studies were applied to other organisations in the industry, a larger scale reduction in environmental impact could be achieved in the short-term. In the longer term, consideration of environmental impact will focus on the types of material used.

References

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CHAPTER 5: POTENTIAL BIODEGRADABLE ALTERNATIVES TO CONVENTIONAL POLYMERS

5.0 Potential Biodegradable alternatives to Conventional Polymers

The aim of this part of the project is to assess the technical performance of some commercially available biodegradable polymers and to compare these with Pactiv's current portfolio of oil-based polymers in order to assess their suitability as alternatives to the materials currently used. A comparison of physical and mechanical properties has been made in section 5.1, while the processability of the biodegradable polymers is assessed in section 5.2.

5.1 Assessment of Technical Performances of Biodegradable Polymers compared to Oil-based Polymers.

The technical properties of two biodegradable polymers, PLA and Materbi, are compared to those of a range of materials currently used at Pactiv UK. These mechanical and physical properties are essential if the biodegradable polymers are to be viable as an alternative.

The current materials tested include APET, both bath-coated and master batch formulations, PVC master batch, PP and PiPS A and PiPS B. PiPS is a combination of PP rework and PS rework. The bath-coated and master batch both refer to the silicon additive, which causes a non-stick effect and is necessary in order to assist the separation of the food packaging containers. This is particularly important when using automated packaging lines. The extruded film is passed through a bath of silica after extrusion, hence the name 'bath coated', whereas the master batch incorporates the additive in the mixing phase prior to extrusion.

5.1.1 Evaluation of Optical Properties

The clarity of colourless materials is important to Pactiv's customers, given that packaging must help sell the product it is protecting. A pack that is supposed to be colourless to the human eye, but that has a yellow tinge to it can hinder sales if the supermarket customer consequently perceives the packaged product to be past its best.

The clarity of samples of the oil-based polymers APET, PP and PVC and the biodegradable polymer PLA were measured for a given gauge thickness using a Coloursphere from Sheen Instruments UK. The instrument accurately measures the colour and clarity of film. The increasing shades of yellowness on the y–axis are measured in points: the higher the values on the y-axis the more yellow and the less clear the samples. Various material types and grades were investigated, as shown in Figure 5.1. Materbi SGC 2763 is a translucent material and thus no attempt was made to test the transparency.

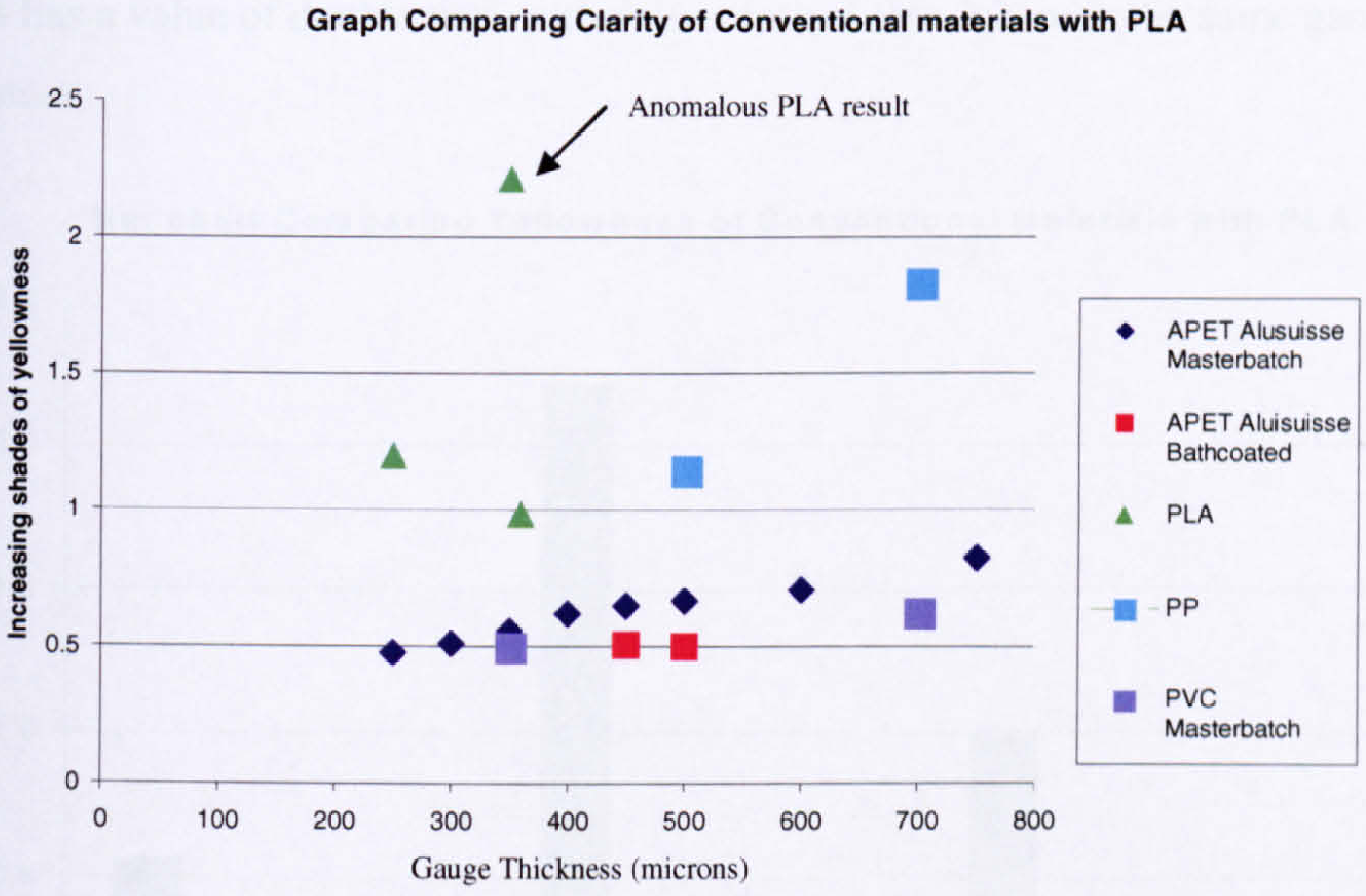

Figure 5.1: Graphical colour comparison of oil based polymers versus biodegradable polymer, PLA

With the conventional polymers, it is clear that clarity of the sheet decreases with increasing gauge thickness. This is demonstrated more systematically by the APET materbatch sample for which a wide range of sheet thicknesses were available.

Figure 5.1 also shows an anomalous PLA result, which could be explained by the samples coming from different batches and producers, with different additives to prevent sticking.

The clarity of bath-coated APET shows a marked decrease in yellowness and resulting increase in clarity, when compared with the masterbatch APET. Bath-coating is the preferred method of adding the non-stick agent silicon to enhance the clarity.

The biodegradable polymer, PLA, is more yellow in colour than most current oil based polymers, the exception being PP (Polypropylene).

Figure 5.2 shows a bar chart comparing the yellowness of two PLA formulations from different producers with Pactiv's standard oil-based polymers APET and PLA masterbatch. The PVC and APET masterbatch are both 350 microns thick and Fig 5.2 shows them as having a similar degree of yellowness, approximately 0.5, whereas PLA has a value of double that, with values from 1.0 to 2.2, with the same gauge thikness.

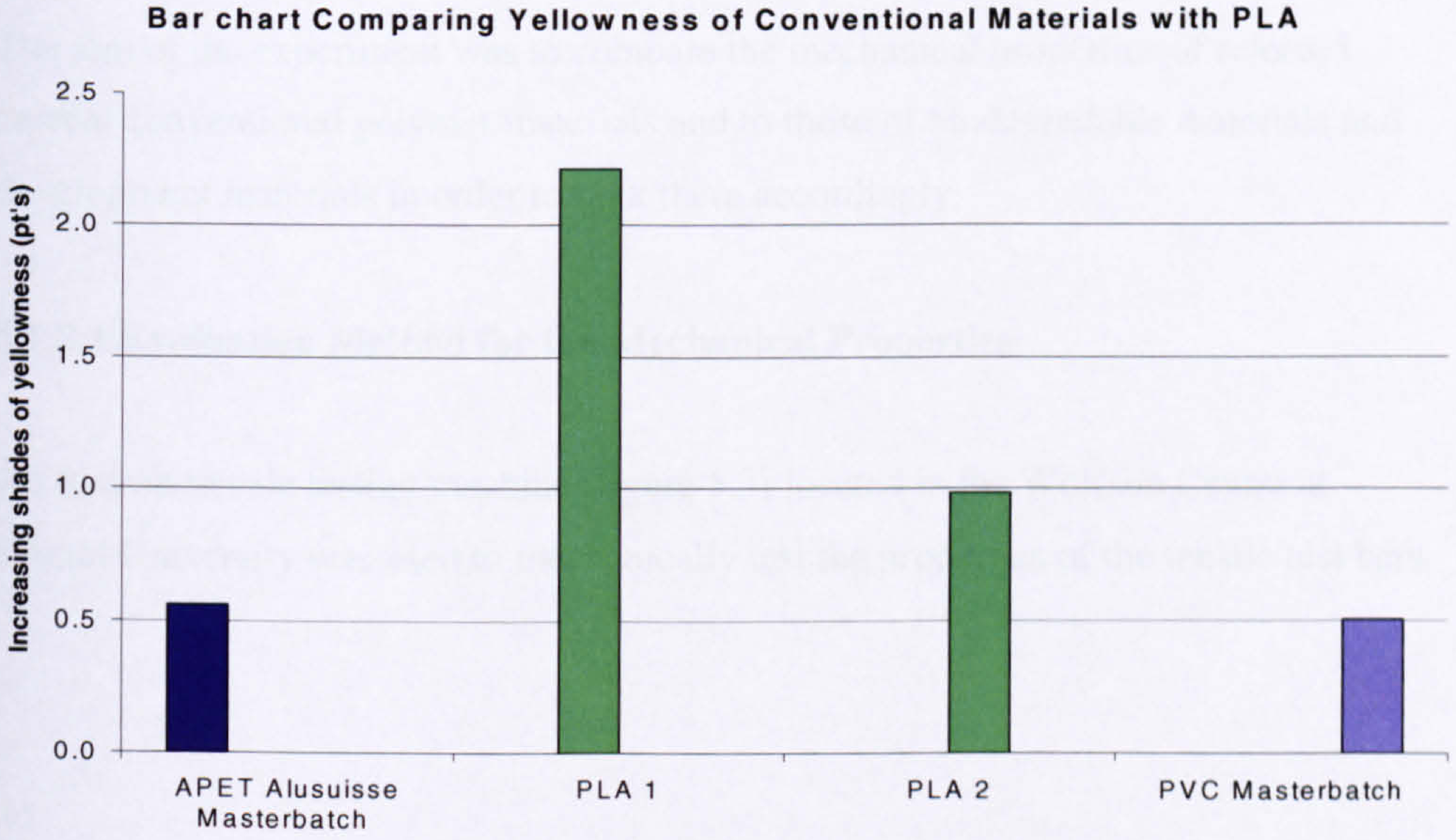

Figure 5.2: Bar chart comparing the yellowness of oil based polymers with biodegradable polymer PLA

This required further investigation and production standards were subsequently established, including using a blue masterbatch which reduces the shade of yellow.

The results show that PLA is almost twice as yellow as Pactiv's current products which are colourless to the human eye, APET and PVC, and customers find this inferior optical property unacceptable in addition to the fact that PLA is more expensive. Pactiv have therefore requested a sample of PLA with a blue tint added to it, which makes the material appear colourless, rather than yellow.

Cargill Dow have claimed that further industrial trials have resulted in the development of expanded PLA and multilayer materials, which have improved mechanical and physical properties to allow the product to be used in relatively high humid conditions, for example, the storage of fresh products and wet products such as meat and fish. An inquiry has shown that these materials have the potential to replace conventional polymers such as PVC, PS or PET. The next stage for Pactiv is to obtain samples of the multilayer material for laboratory and production trials.

5.1.2 Evaluation of Mechanical Properties

The aim of the experiment was to compare the mechanical properties of selected current conventional polymer materials and to those of biodegradable materials and development materials in order to rank them accordingly.

5.1.2.1 Evaluation Method for the Mechanical Properties

An Instron tensile testing machine (figure 5.3) located in the Wolfson Centre at Brunel University was used to mechanically test the properties of the tensile test bars.

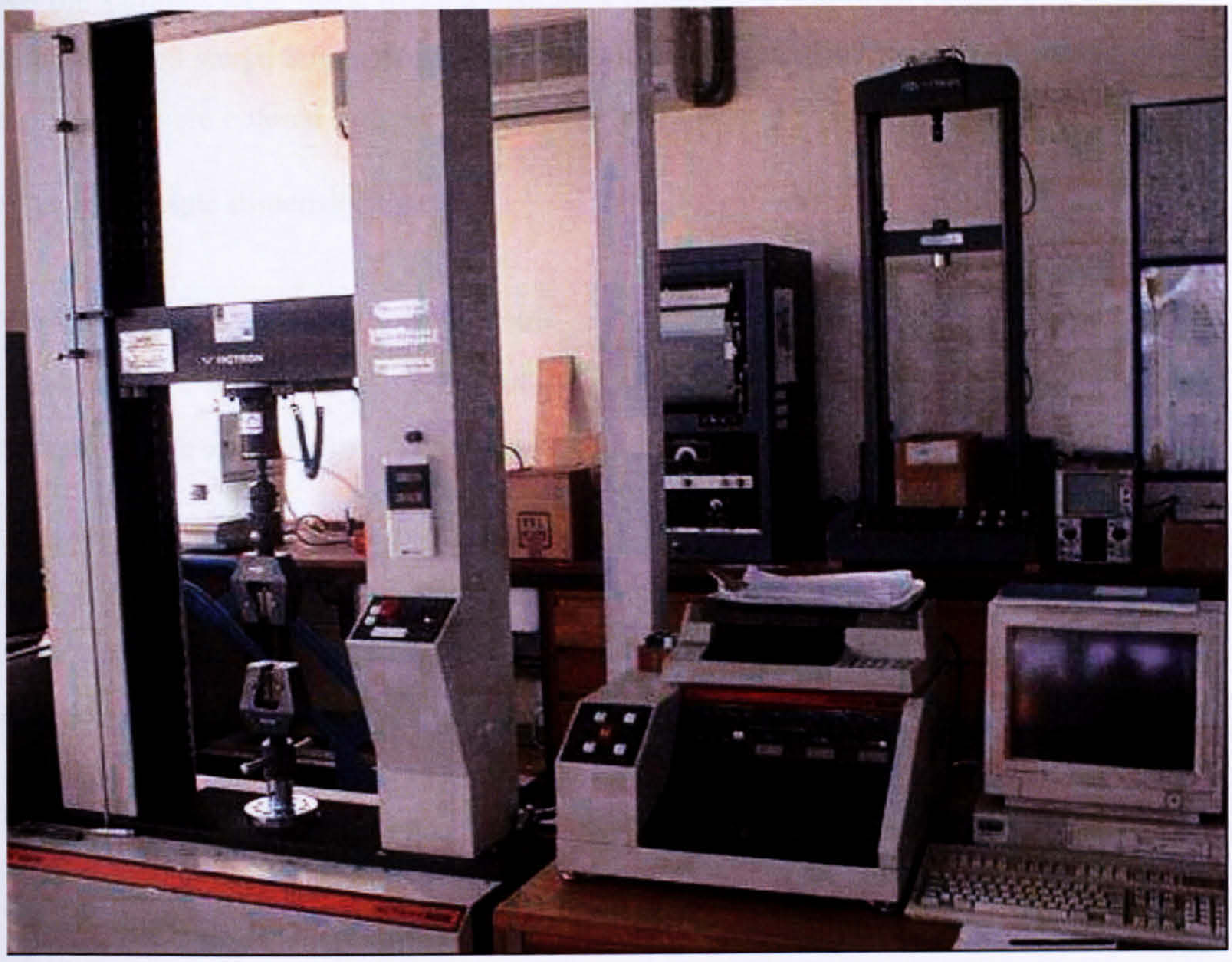

Figure 5.3: Instron equipment similar to that used for tensile testing.

The machine was operated in accordance with the BS standards: BS 2782: part 3 method 321:1994- ISO 527-2:1993, but a crosshead speed of 50 mm/min was used rather than the standard 5 mm/min, to reduce the test time. The following test conditions were used:

Humidity = 50 % ± 2%
Crosshead speed = 50 mm/min ± 0.1mm/min
Temperature = 23°C ± 1°C

All the samples were made using a hydraulic press and a dumbbell cutter. The width, thickness and gauge length of each sample was measured using digital callipers, and the results were entered into the computer prior to testing.

Average sample dimensions were:

Width = 10.2 mm ± 0.05mm
Thickness = 0.6 mm ± 0.4mm
Gauge Length = 77.0 mm ± 0.05mm

Five samples were prepared for each material. The samples were secured to the Instron tensile testing machine using the method as stated in the manual. The samples were tested to their point of failure. The results of the applied load versus displacement were converted to stress and strain to obtain the mechanical properties.

5.1.2.2 Results and Discussion

5.1.2.2.1 Tensile Modulus

Table 5.1: Tabulated results of the tensile modulus of samples

	Tensile Modulus (MPa) (±0.005)				
Sample	1	2	3	Average	Standard Deviation
PVC	755.92	565.81	733.31	685.01	103.85
PP	267.55	226.02	206.93	233.50	30.99
PS	585.72	543.87	616.89	582.16	36.64
APET	889.74	840.77	838.01	856.17	29.10
PLA	1002.65	1068.59	1514.96	1195.40	278.70
PiPS (A)	160.4	352.63	205.62	239.55	100.51
PiPS (B)	179.44	183.68	214.66	192.59	19.23
Materbi	113.57	220.76	178.56	170.96	54.00

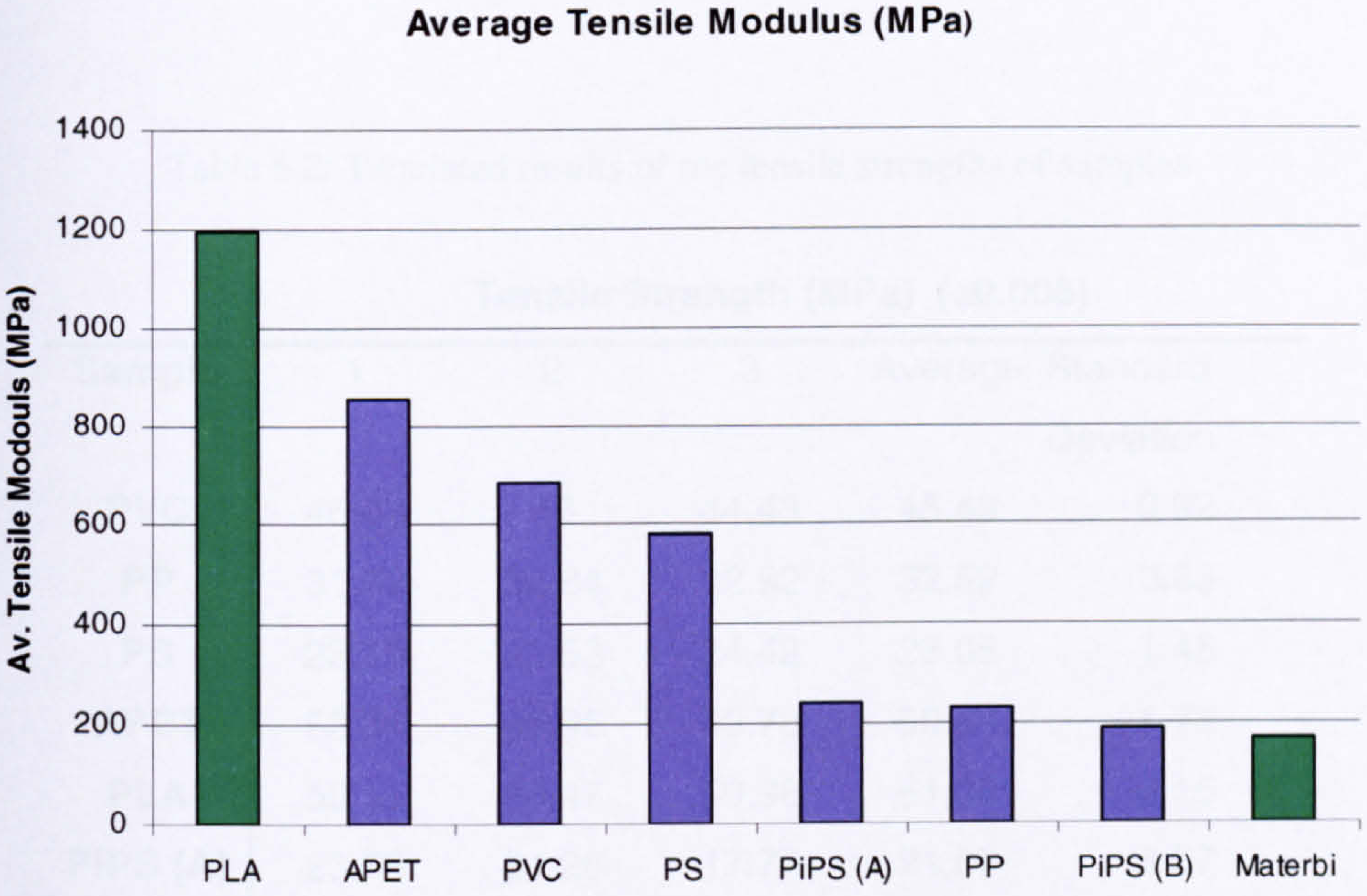

Figure 5.4 Graphical representation of the averaged tensile modulus

The results show that PLA is significantly more rigid and that Materbi is less rigid than conventional polymers used currently at Pactiv UK. This suggests that PLA would be a suitable material in terms of enhancement of rigidity for the thermoformed food trays or that a lower gauge may be considered. The Materbi material is more comparable to PP and could be used for more flexible applications.

5.1.1.2.2 Tensile Strength

Table 5.2: Tabulated results of the tensile strengths of samples

	Tensile Strength (MPa) (±0.005)				
Sample	1	2	3	Average	Standard Deviation
PVC	46.03	46	44.43	45.49	0.92
PP	31.79	32.84	32.92	32.52	0.63
PS	23.19	21.53	24.42	23.05	1.45
APET	52.85	49.95	49.78	50.86	1.73
PLA	59.55	63.47	59.98	61.00	2.15
PiPS (A)	23.58	24.26	17.77	21.87	3.57
PiPS (B)	22.8	23.31	17.99	21.37	2.94
Materbi	18.73	21.3	17.99	19.34	1.74

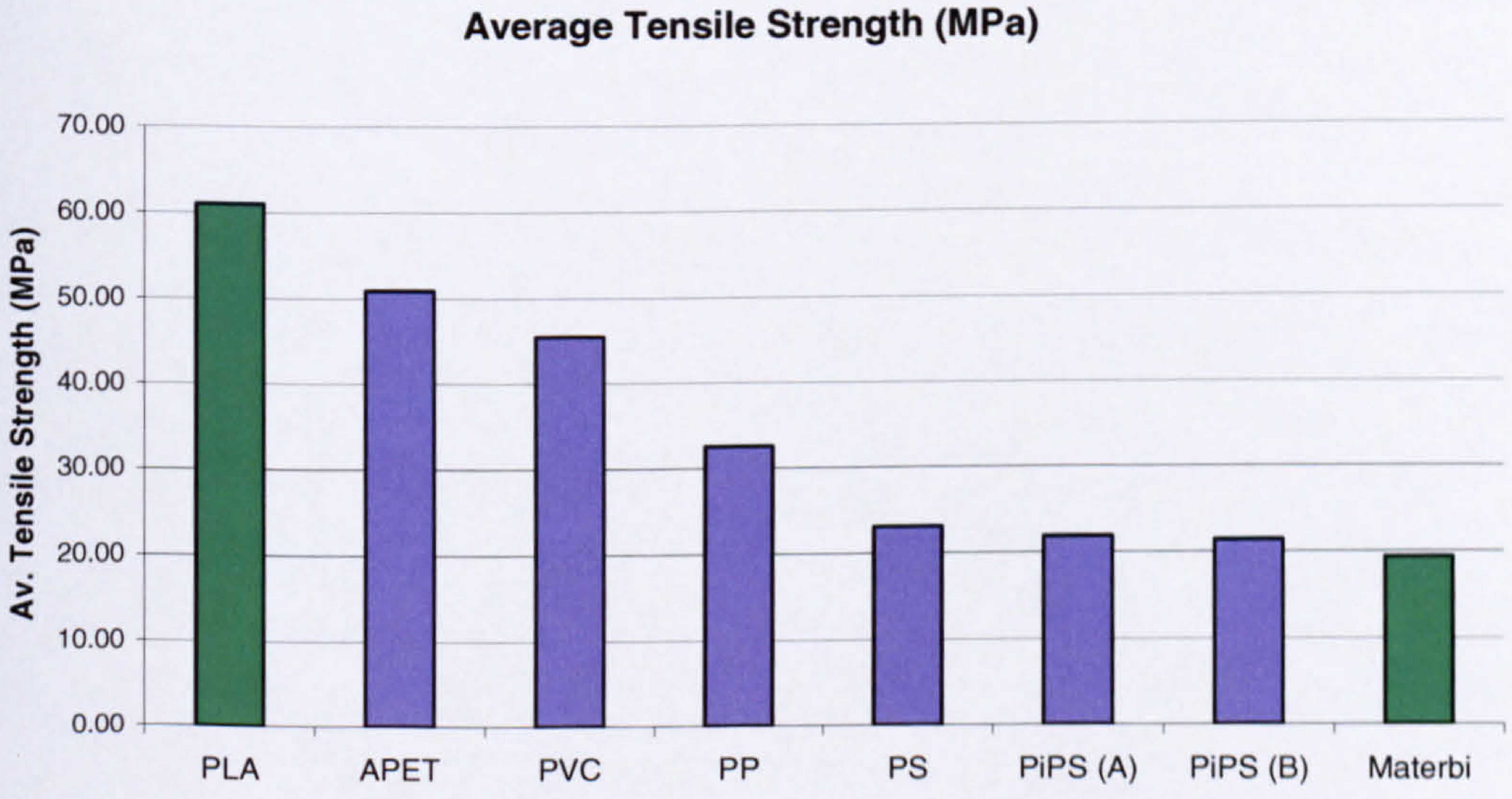

Figure 5.5: Graphical representation of the averaged tensile strengths

The results of figure 5.5 show that PLA has a higher tensile strength and that Materbi has a lower tensile strength compared to conventional polymers used currently at Pactiv UK. This suggests that the PLA would be a suitable material in terms of enhancement tensile strength for the thermoformed food trays or that a lower gauge may be considered. The Materbi material has a lower tensile strength than PP which will have to be taken into consideration when designing thermoformed products.

5.2 The assessment of processability of biodegradable polymers and the addition of biodegradable additives to Polypropylene.

In this section, the processability of two commercially available biodegradable packaging materials: PLA and Materbi SGC 2763 are investigated. Granulated Materbi material was tested in terms of extrusion processability and PLA sheet material was investigated in terms of thermoformability. Finally, additives to assist the biodegradation of conventional polymers were extruded with polypropylene to understand their effect on sheet extrusion and compostability.

5.2.1 The Extrusion Trails on Materbi SGC 2763

The Materbi SGC 2763 material from Novermont was extruded on a lab scale to evaluate its potential for further sheet extrusion testing on a commercial scale.

5.2.1.1 Description of the lab scale extrusion process

A Betol twin-screw extruder, located in the Wolfson Centre at Brunel University, with co-rotating non-intermeshing screw was used (Fig. 5.6 and Fig 5.7). It has four different temperature zones along the length of the screws, which were adjusted to the processing temperatures recommended by Novermont and then kept constant through the experiment. The die has a separate temperature control, which is usually set slightly higher that that of the four zones. The twin-screw extruder was purged using a talc filled PVC to avoid contamination from previously extruded materials.

The Materbi pellets were fed into the extruder. The co-rotating system allows the material to be transferred from one screw to the other in a figure of eight pattern, which enhances material mixing. In order to avoid potential blockage the granules were added slowly at first until a steady flow was achieved. A water-cooled twin roller was used as a haul-off for the extruded sheet.

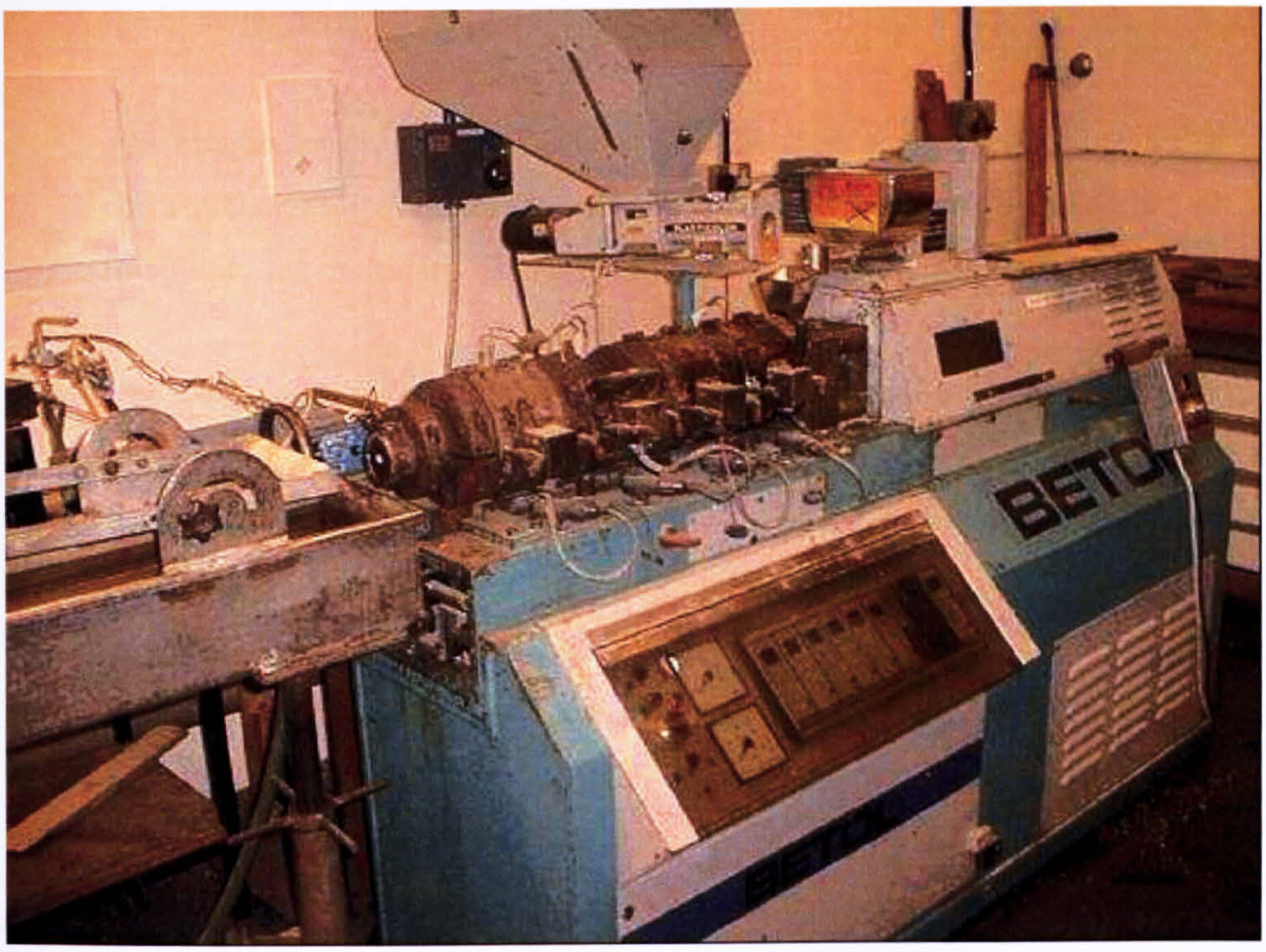

Figure 5.6: The Betol Twin extruder

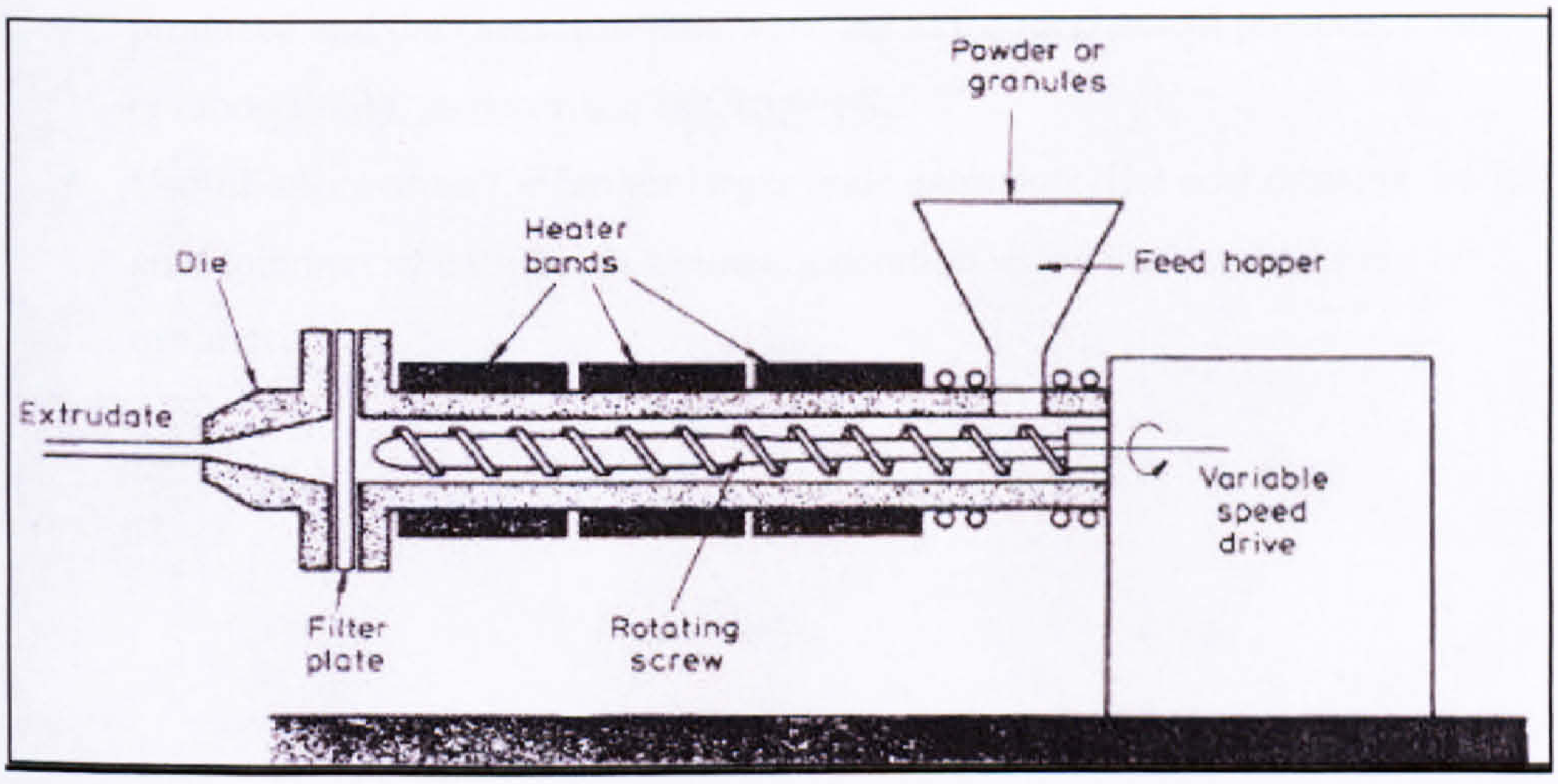

Figure 5.7: Schematic diagram of an extruder, similar to that used in this work [1]

5.2.1.2.1 Materbi SGC 2763 Observations and Results

- An unusual sweet smell was noted during the experiment, which suggests that the biodegradable additive maybe be sugar.

- The extrudate from the die was tacky and therefore a water-cooled roller haul off was found important as there needs to be a high degree of heat extraction to solidify the extrudate. This is a limiting factor in the extrusion process.

- The water cooled haul-off rollers produced a high degree of gloss on one side of the material. This is the case when extruding other conventional materials such as PP and suggests that suitable processing conditions were achieved.

- A visual check of the material suggested that a suitable quality of film had been produced and therefore further tests were carried out.

In summary the experiment was a success in the following aspects:

- Quality of sheet extrudates: Acceptable extruded sheet materials were produced and the sheet materials were tested for mechanical properties and compostability, as described in Chapter 8.
- Useful information for further larger scale extrusion: The cost of using the full size commercial extruder at a slower operation speed than normal must be evaluated.

5.2.2 The Thermoforming Trails of PLA

Pactiv have carried out successful industrial trials using PLA. The Research Engineer produced an article for the Plastic and Rubber Weekly (PRW), which is attached in Fig 5.8.

A natural choice

A RANGE of thermoformed 'natural' compostable packaging has been developed by Pactiv FoodService-Packaging Europe using NatureWorks material from Cargill Dow. The physical properties of the new range are said to be between those of APET and PS.

NatureWorks is manufactured from polylactic acid (PLA) derived from sustainable carbon harvested from plants such as corn.

Pactiv's range includes thermoformed trays, hinged packs and confectionery selection packs.

They are said to have an impact resistance, rigidity and clarity comparable to oriented polystyrene and a service temperature and density close to that of APET.

NatureWorks has also been used by Autobar Disposables Group, of Brentford, for compostable thermoformed containers introduced in Italy earlier this year (*PM*, June 20).

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Figure 5.8: Pactiv press release

5.2.3 Use of Biodegradable additives in Polypropylene

Biodegradable additives initiate and accelerate polymer degradation. When the polymer is disposed of in either a compost or landfill site, the bio-additive catalyses the oxidation and a chain scission occurs, reducing the molecular weight of the polymer and enabling biodegradation to occur.

The Bio-additives (BA) were sourced from Wells Plastic, Staffordshire, UK and from Biotech, Sweden. Both grades are compatible with Polypropylene (PP) and hence two grades of PP Homopolymer and Co-polymer from Dow Chemicals, UK were selected for this trial to see if the additives enhance biodegradation of PP and to assess the effect on the processing and performance of the modified materials. Chalk or granulated calcium carbonate, Omyalene 102, Omya UK was also added to improve mechanical and surface properties such as scratch resistance. Chalk can be added up to 40 weight % to improve stiffness, tensile strength and creep resistance [2]. The gauge of the material could be reduced by 15 – 20% due to the increase in stiffness. Disadvantages include the necessity for regular cleaning of the extruder barrel and screw. The thermoforming-hit rate should increase, given that less heat would be required.

The leadership team at Pactiv decided not to develop this any further.

5.2.3.2 The Extrusion Compounding Procedure

The materials formulations are listed in Table 5.3 and are based on recommendations from the suppliers. They are designed to test the effect of composition variation of the Polypropylenes, Bio additives and Chalk combinations, all of which were measured, hand blended and stored overnight in a sealed bag.

A Betol BTS40 co-rotating twin screw extruder with non-intermeshing co-rotating screws was used (figure 5.9). The extruder contains mixing discs and reverse-flow screw configurations, which enhance the homogeneity of compounding. The twin-screw extruder has five different temperature zones along the length of the screw that are electrically heated and water-cooled to keep a constant processing temperature throughout the experiment.

The extruder was purged using a Polypropylene purge prior to the compounding of the blends. A twin-screw feeder was used to feed the various blends into the feeding pot.

Table 5.3: The materials formulation of the batches for extrusion compounding (wt%)

Blend No.	Blend Composition
PP	80wt% Polypropylene (PP) homo & 20wt% PP co
Z1	76wt% PP homo, 19wt% PP co & 5wt%Bio-Additive (BA)
Z2	72wt% PP homo, 18wt% PP co & 10wt% BA
Z3	68wt% PP homo, 17wt% PP co & 15wt% BA
Z4	76wt% PP homo, 19wt% PP co & 5wt% BA
Z5	72wt% PP homo, 18wt% PP co & 10wt% BA
Z6	68wt% PP homo, 17wt% PP co & 15wt% BA
Z7	48wt% PP homo, 12wt% PP co, 10wt% BA & 30 wt% Chalk

During extrusion the screw speed was set constant at 112 rpm. The material feeding rate was set a 6kg/hr. The set and actual barrel temperature profiles during extrusion are shown in Table 5.4. The variation in motor loading and die pressure are listed in Table 5.5.

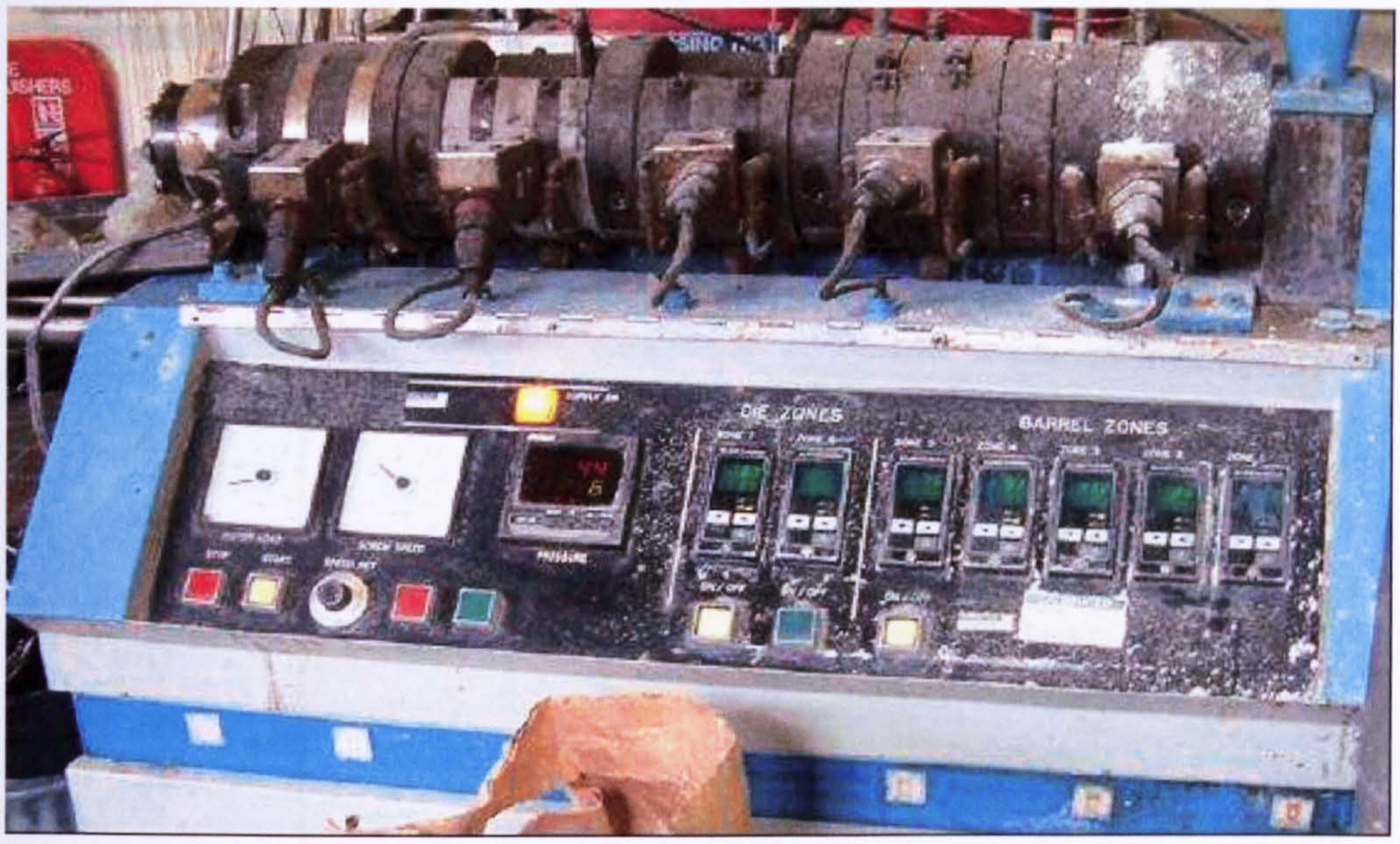

Figure 5.9: Dassett extruder used for this trial

Table 5.4: The set and actual temperature profiles from the die barrel, to barrel one near the feeding pot during the Extrusion Process

Blend No.	Die Zone 7 (°C) (±2)	Die Zone6 (°C) (±2)	Barrel Zone 5 (°C) (±2)	Barrel Zone 4 (°C) (±2)	Barrel Zone 3 (°C) (±2	Barrel Zone 2 (°C) (±2)	Barrel Zone 1 (°C) (±2)
Set	170	200	200	180	160	120	80
PP	179	200	200	178	167	120	81
Z1	176	200	200	185	149	117	81
Z2	177	200	200	183	155	119	81
Set	170	190	180	180	160	120	80
Z3	172	190	196	180	166	134	84
Z4	170	190	190	176	158	124	94
Z5	170	190	190	188	157	121	85
Z6	168	190	191	176	161	120	82
Z7	167	190	192	178	159	120	80

The parameters for the feeder setting, motor load, screw speed and die pressure were recorded for each blend.

Table 5.5: Parameters for the Extrusion Process

Blend No.	Motor Load (Amps)	Die Pressure (Psi)
PP	8	74
Z1	8	72
Z2	8	74
Z3	8	70
Z4	7	68
Z5	7	64
Z6	6	68
Z7	6	64

The die has a separate electrical temperature control without water-cooling. It is usually set at a slightly higher temperature than that of the five zones and is kept constant through the experiment. During extrusion the barrel temperature profile and water constant relative to solid and machine rotation speed were kept constant. The percentages of polypropylene, bio additives and chalk were varied in order to determine the desired range.

5.2.3.3 Results and Discussion

- The trials proved that it is possible to extrude Pactiv's polypropylene blend with the addition of biodegradable additives and chalk fillers.
- The resultant extrudate was of a similar quality to Pactiv standard blend of PP
- The optical experiment showed that unlike conventional oil based polymers (APET and PVC) PLA's clarity is not dependent on its thickness, this maybe due to the addition of masterbatch to disguise its natural yellow colour.
- The mechanical testing concludes that PLA is a more rigid material, which is an important property as it enables Pactiv to down gauge products, making PLA more cost competitive to its oil-based alternatives.

- The trials conclude that whilst is it possible to extrude Materbi, the poor mechanical properties combined with high material costs make it a poor competitor to oil-based alternatives.

5.3 Summary

The chapter concludes that PLA is the only potential alternative to current oil-based polymers, takes Pactiv a step forward to understanding the processing of these materials from granule form to extruded sheet using its production facilities which paved the way towards the ultimate goal of adopting a sustainable, biodegradable, thermoformable, affordable material for production of food packaging trays.

References

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[1] Hull D. Clyne T. W (1996) An Introduction to Composite Materials 2nd Edition, Cambridge University Press, ISBN 0-531 38190 8.

[2] www.omya.com

CHAPTER 6: DEVELOPMENT OF NOVEL STARCH BASED MATERIALS

6.0 Development of Novel Starch based Materials

Starch is of little use on its own due to its poor mechanical properties, difficulties in processing and sensitivity to water. It is however a low-cost feedstock with inherent biodegradability. Different types of starch have been used to produce biopolymers by compounding with additives such as plasticizers. This produces synthetic or natural biodegradable polymers with enhanced properties whilst maintaining the characteristic of biodegradability [1].

6.1 Aims and Objectives

Pactiv UK Thermoforming is particularly interested in rigid materials. Initially the research focused on materials that could be extruded and formed on Pactiv's existing machinery. Transparent sheet materials are highly desirable in the food packaging industry. However, most of the commercially available starch-biopolymer compounds are translucent.

6.1.1 Aim

The aim of this work was to carry out a feasibility study for developing transparent biopolymer materials, which could be thermoformed into food packaging containers.

6.1.2 Objectives

- To study the processability of wheat starch based biopolymers
- To evaluate the transparency and mechanical properties of the resultant sheet materials
- To carry out preliminary study on formability of the sheet materials into containers
- To provide the foundations for further development of such materials

The feasibility study was carried out at Brunel University. Initial trials were carried out using formulations based on a wheat flour to study the parameters of the extrusion process and the range of properties of the resultant sheet. Combinations of wheat starch, purified wheat starch and formulations of polyvinyl alcohol (PVOH) plasticized with glycerol were studied. These formulations were extruded using a twin screw extruder. The extrudates were compressed into sheet via compression moulding. The mechanical properties of the sheet materials were characterised and their formability via vacuum forming into a food packaging tray studied.

This feasibility study proved the concepts of the development set in the objectives and led to a full scale project undertaken by Brunel University in a DEFRA Foodlink project in collaboration with Pactiv UK and other industrial and research partners.

6.2 Materials and Formulations

The following materials were used in the formulations shown in Table 6.1:

- Temple wheat flour from Haygates Ltd, Northampton, UK
- Purified wheat starch (Meritena 200) distributed by Amylyn Europe N.V, Belgium
- PVA C20 from PVAXX cooperation
- PVA C22 with the addition of talc C20 from PVAXX cooperation (Gloucestershire)
- Glycerol (96124) produced by the Dow Chemical Company (Norfolk)
- PVA, NK – 05
- Natural Rubber

Table 6.1: Formulations studied in this work.

Blend No	*Blend Composition*
A1	100 wt % Purified wheat starch (PWS)
A2	90 wt % PWS & 10 wt % Glycerol
A3	85 wt % PWS & 15 wt % Glycerol
A4	80 wt % PWS & 20 wt % Glycerol
A5	95 wt% PWS & 5 wt% Polyvinyl Alcohol (PVA)
A6	90 wt% PWS & 10 wt% PVA
A7	85 wt% PWS, 15 wt% PVA
A8	80.75 wt% PWS, 14 wt% Glycerol & 5 wt% PVA
A9	76.5 wt% PWS 14 wt% Glycerol & 10 wt% PVA
A10	72.25 wt% PWS, 13wt% Glycerol & 15 wt% PVA
A6-2	95 wt% PWS & 5 wt% C 320
A5-N	95 wt% PWS & 5 wt% Natural Rubber (NR)
B0	100 wt % Wheat Flour
B1	85 wt % Wheat Flour & 15 wt % Glycerol
B2	85wt% Blend No.B1 & 15 wt % Pvaxx C20
C1	94 wt % Wheat Flour & 6 wt % Pvaxx C20
C2	88 wt % Wheat Flour & 12 wt % Pvaxx C20
C3	76 wt % Wheat Flour & 24 wt % Pvaxx C20
C4	94 wt % Wheat Flour & 6 wt % Pvaxx C22
C5	88 wt % Wheat Flour & 12 wt % Pvaxx C22
C6	76 wt % Wheat Flour & 24 wt % Pvaxx C22

6.3 Experimental Details

6.3.1 Materials preparation

The PVAXX granules were ground into powder using a heavy duty, high speed twin blade grinder to enhance the uniformity of compounding.

The various blend compositions (see Table 6.1) were measured and blended using a Henschel mixer (shown in Figure 6.2) and then stored overnight in separate sealed plastic bags.

Figure 6.1: Henschel high-speed mixer used to blend purified wheat starch, wheat flour, glycerol and PVA combinations

The 100% purified wheat starch blend was hand mixed with 6% water and stored overnight to form agglomerates to enhance the flow of the material and prevent bridging in the feeding unit and on the extruder screw.
The wheat flour blends were passed through the screw feeder to break down any large agglomerates.

6.3.2 Calibrations of materials feeding

For accurate control of material feeding, the screw feeder was calibrated for each blend to determine the mass flow rate of the blends through the feeder at different settings, by measuring the amount of material conveyed in a set period of time (Figure 6.2 shows the calibration curves used).

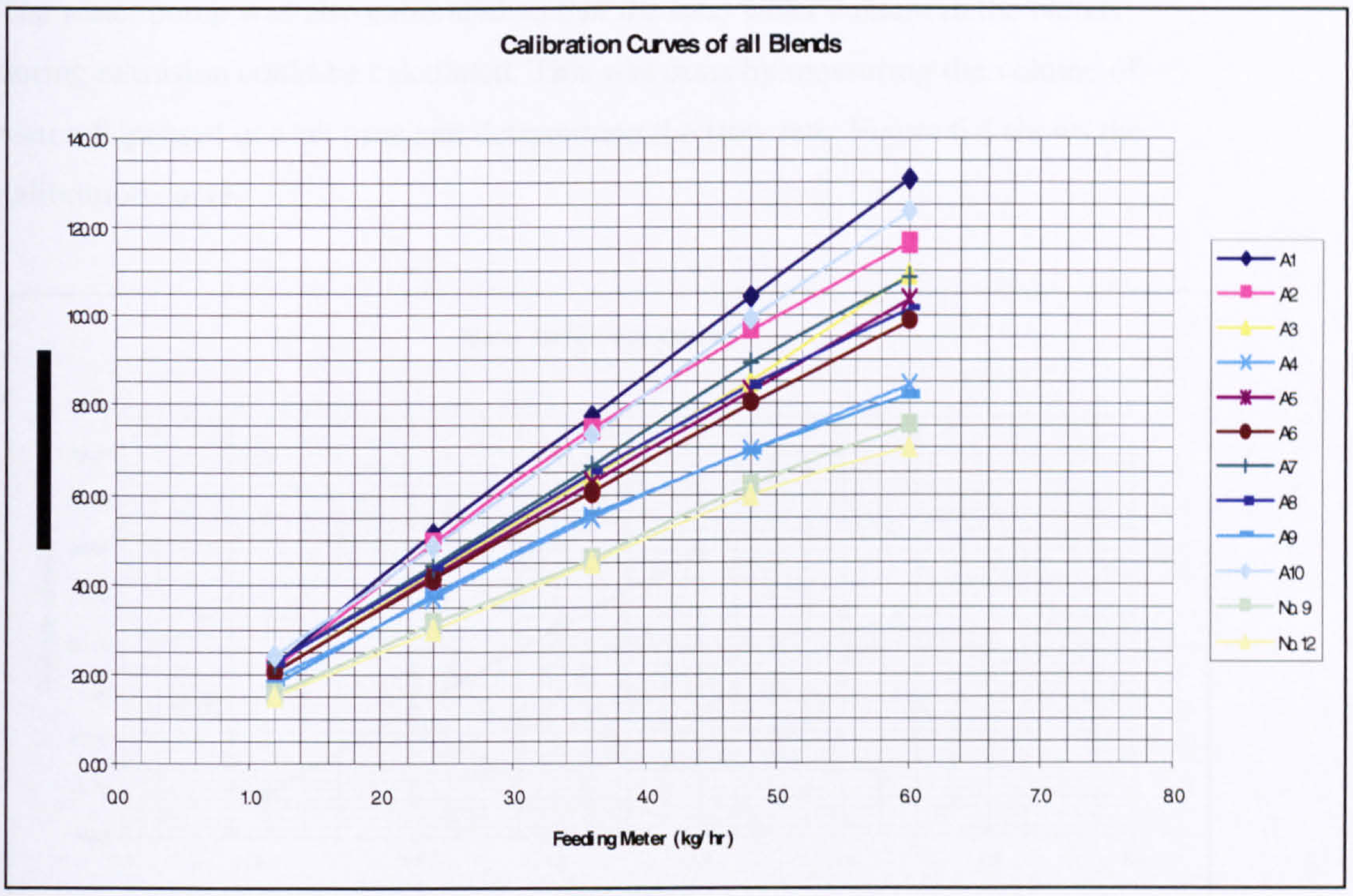

Figure 6.2: Calibration curves for feed rates of the blend combinations.

Water was added to the second barrel of the extruder using a dispenser pump (shown in Figure 6.3) as a water pump.

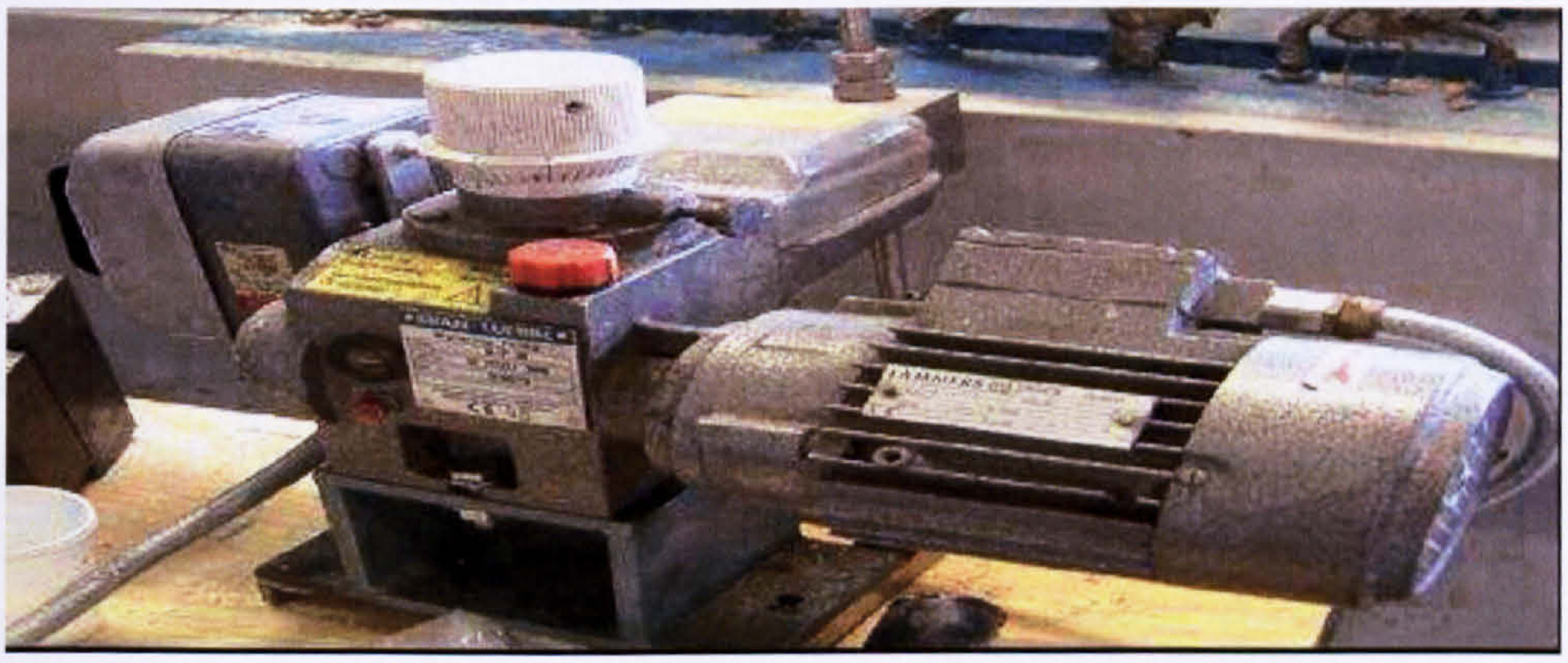

Figure 6.3: Water Pump

The water pump was also calibrated so that the total water content in the blends during extrusion could be calculated. This was done by measuring the volume of water dispensed in a set time and determining the flow rate. Figure 6.4 shows the calibration curve.

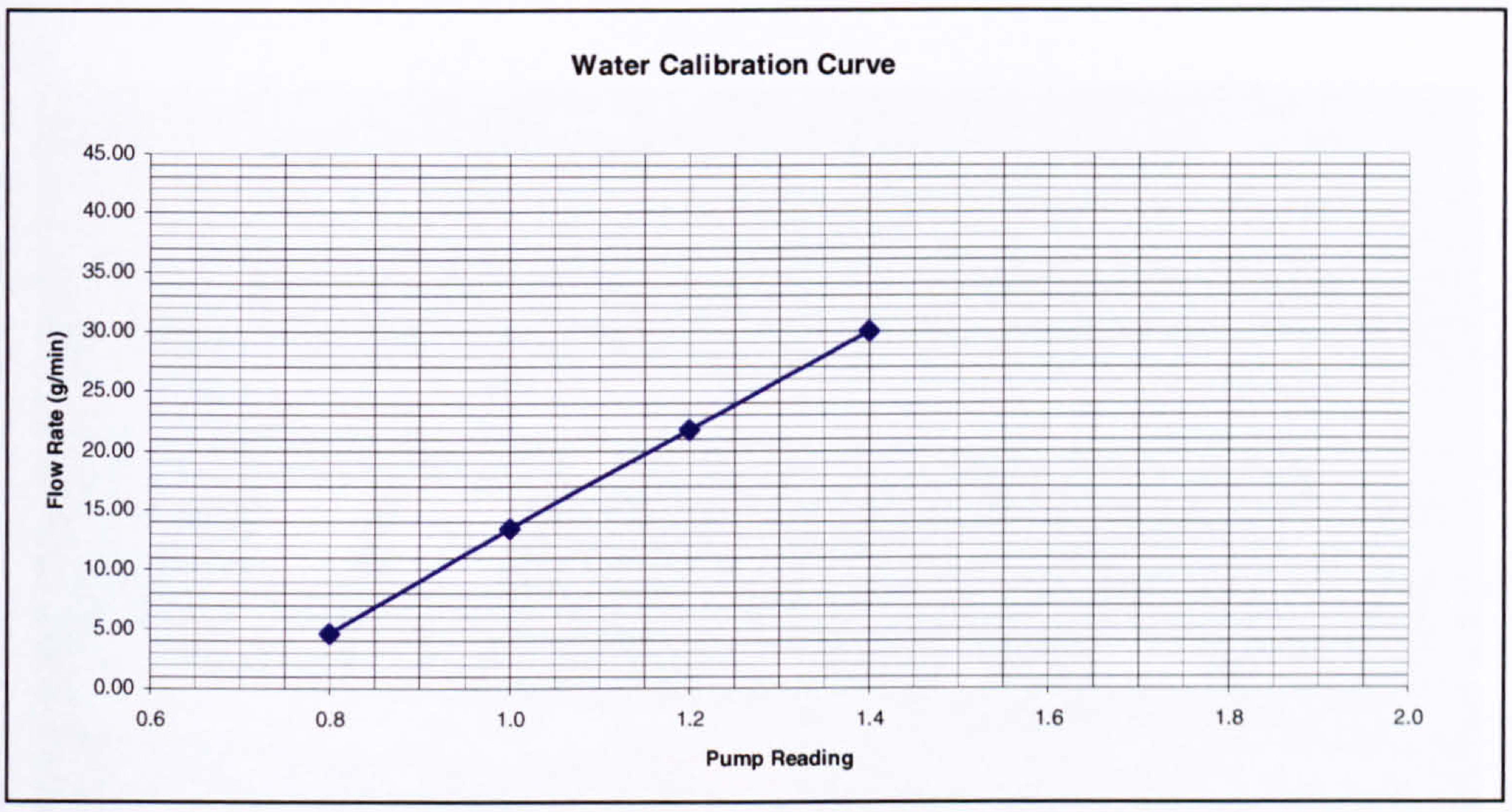

Figure 6.4: Calibration curve for water

6.3.3 Extrusion

A Betol BTS40 co-rotating, twin screw extruder (shown in Figure 6.5) with non-intermeshing co-rotating screws was used for extrusion of the blends. The extruder was always purged using wheat flour prior to extrusion of a different blend. A twin screw feeder was used to feed the various blends. Water was added directly into the second barrel of the extruder using a dispensing pump. A schematic diagram of a similar extruder is shown in Figure 6.6. The co-rotating system allows the materials to be transferred from one screw to the other in a figure of eight pattern to enhance blending. The extruder also contains mixing discs and reverse-flow screw configurations, which enhance the homogeneity of compounding. The twin-screw extruder has five temperature zones running along the length of the screw, which are electrically heated and water-cooled to keep a constant processing temperature profile throughout the experiment. The die has a separate electrical temperature control, only without water-cooling. The die temperature was also kept constant through the experiment. During extrusion the following parameters were set: the barrel temperature profile, the proportion of water was kept constant relative to the proportion of solid and machine rotation speed. All these parameters were kept constant. The percentages of glycerol, PVA, purified wheat starch, rubber and impact modifier, were varied to the desired range.

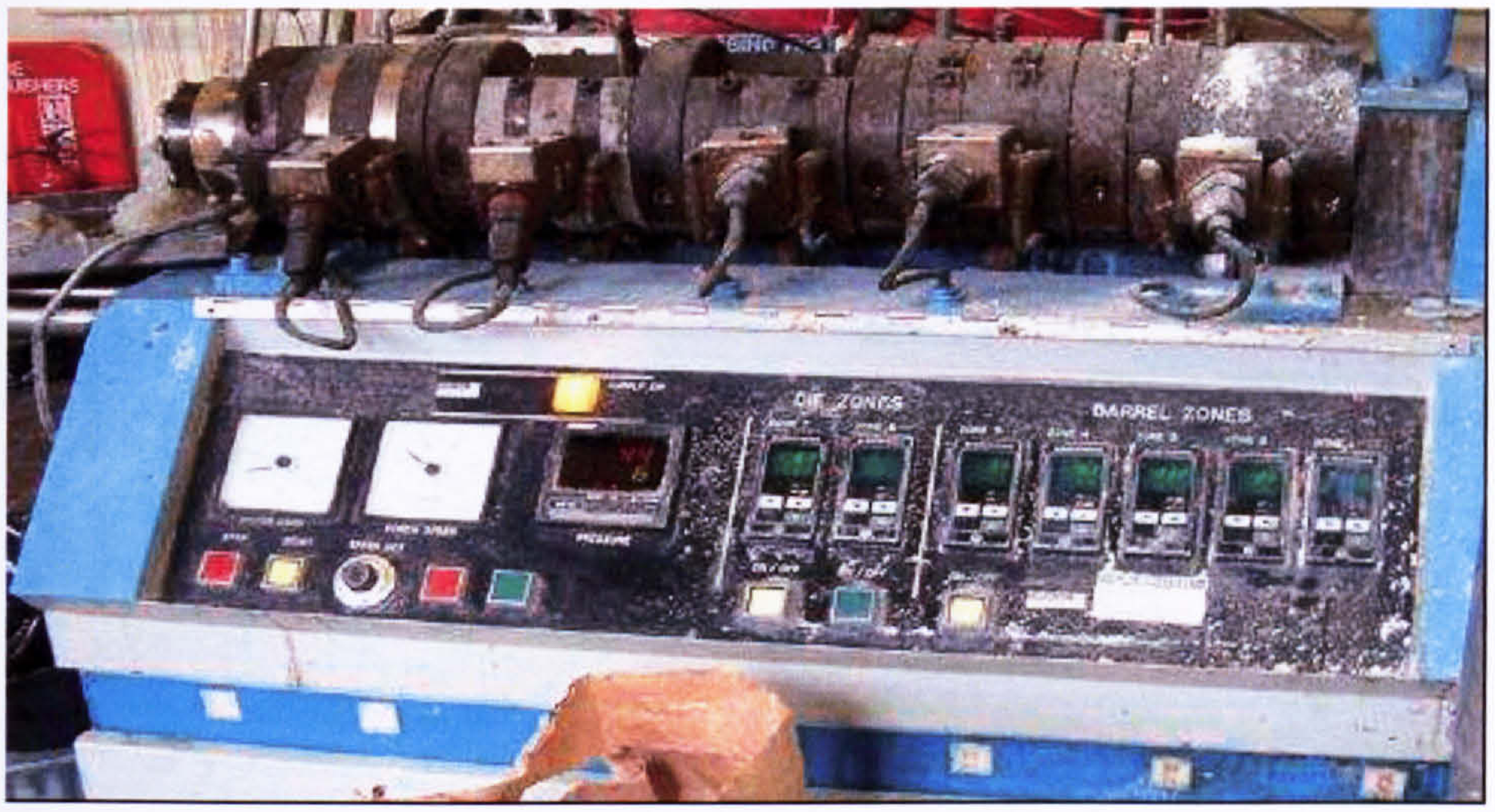

Figure 6.5: Betol extruder used for trials.

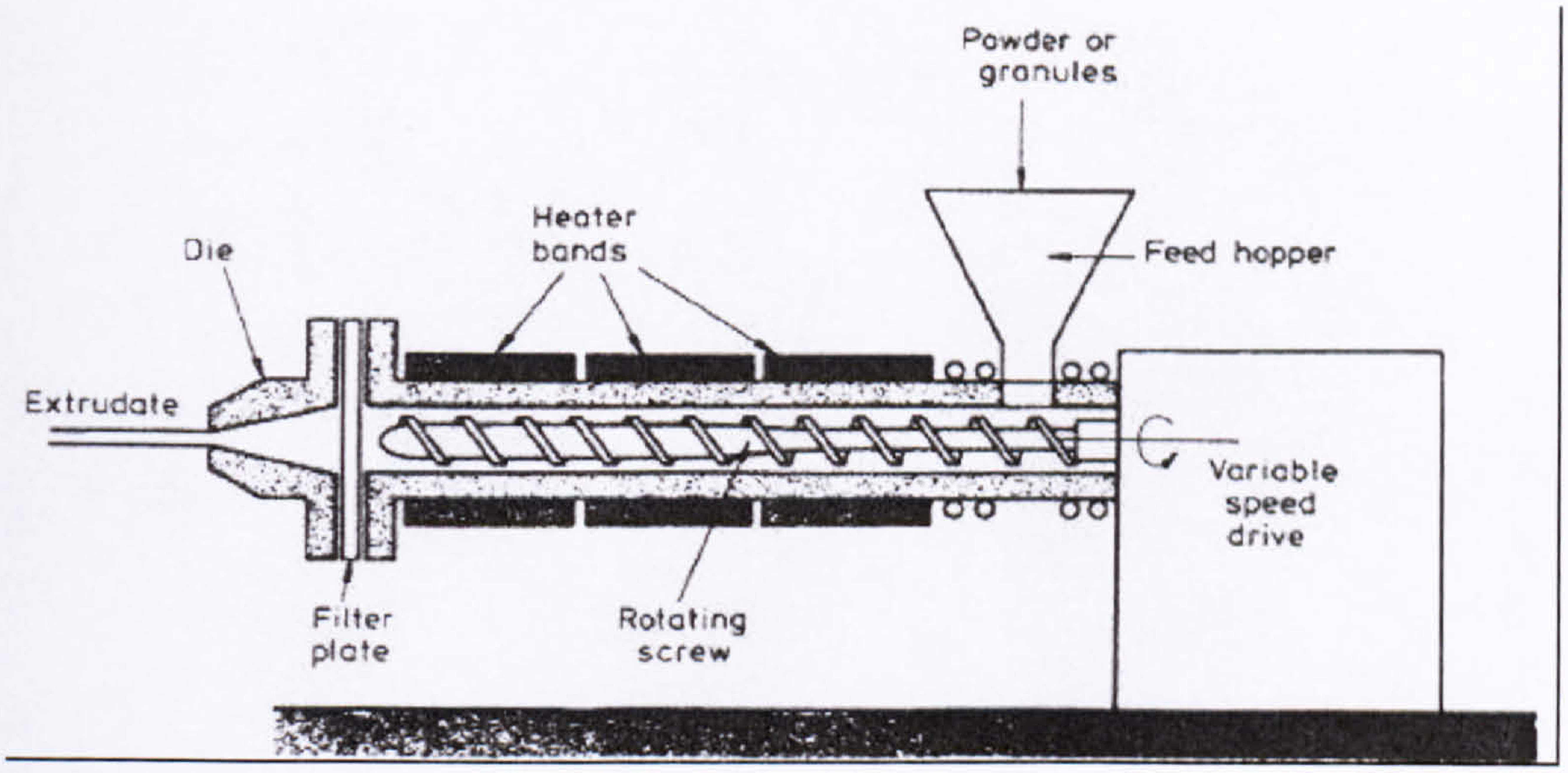

Figure 6.6: Schematic diagram of an extruder

Length (mm)	120	150	90	35	150	120	45	80	80
Pitch (mm)	24	24	24	T	24	16	M	16	16

Barrels	F	Barrel 1	Barrel 2	Barrel 3	Barrel 4	Barrel 5

T – tri-lobal; M – mix disc; F – feed hopper.

Figure 6.7: Screw Configuration in the Extruder

Table 6.2: Temperature Parameters for the Extrusion Process.

Blend No.	*Die Zone 7 (℃) (±2)*	*Barrel Zone 5 (℃) (±2)*	*Barrel Zone 4 (℃) (±2)*	*Barrel Zone 3 (℃) (±2*	*Barrel Zone 2 (℃) (±2)*	*Barrel Zone 1 (℃) (±2)*
Set	**50**	**75**	**85**	**120**	**80**	**60**
A1	68	75	92	120	84	60
A2	72	75	92	121	80	60
A3	71	75	93	121	80	59
A4	69	75	93	119	81	60
Set	**60**	**75**	**85**	**130**	**80**	**60**
A5	69	75	92	129	81	60
A6	72	73	93	127	85	62
A7	73	76	93	129	87	60
A8	70	75	95	129	89	60
Set	**60**	**75**	**85**	**120**	**80**	**60**
A9	71	76	94	120	84	60
Set	**60**	**75**	**85**	**130**	**80**	**60**
A10	69	75	94	132	81	61
No. 9	70	75	93	129	88	62
No.12	71	74	92	130	84	62
B0	78	75	91	120	80	60
B1	78	75	91	120	80	60
B2	77	75	96	120	80	60
No.1	80	75	90	120	80	60
No.2	80	75	90	120	80	60
No.3	80	75	90	120	80	60
No.4	80	75	90	120	80	60
No.5	80	75	90	120	80	60
No.6	80	75	90	120	80	60

Note: Zone 1 corresponds to feeding

Table 6.3: Other parameters recorded for extrusion of the blends.

Blend No.	*Motor Load (Amps)*	*Screw Speed (RPM)*	*Die Pressure (Psi)*	*Water Pump Setting*	*Water Flow rate (g/m)*	*Feeder Setting (Kg/hr)*	*Feeder Rate (g/m)*
A1	6	112	40	1.1	17.5	1.95	40
A2	6.5	112	80	1.1	17.5	2.05	41
A3	7	112	49	1.0	13.5	1.85	33
A4	4	112	49	1.2	22	3.35	52
A5	6	112	48	1.2	22	2.30	40
A6	8	112	70	1.2	22	2.35	40
A7	8	112	72	1.3	26	2.15	40
A8	4	112	72	1.25	24	2.20	40
A9	6	112	48	1.0	13.5	2.55	40
A10	8	112	62	1.0	13.5	2.00	40
No.9	9.5	112	102	1.2	22	3.20	42
No.12	4	112	68	1.4	30	2.50	30
B0	7	112	38	1.1	22	2.30	40
B1	7	112	32	1.1	22	2.35	40
B2	7	112	24	1.2	26	2.15	40

6.3.4 Sample Preparations

6.3.4.1 Sheet samples

Sheet materials were prepared by compression moulding. The extrudate of each blend was collected for ~30 seconds in order to obtain a hand-sized ball, with an estimated weight of 100 grams. The ball of extrudate was sandwiched between two 200 micron thick plastic flat sheets and two rigid plastic planks ~2mm thick, as shown in Figure 6.8, and then pressed with a 40 tonne press (Figure 6.9 - manufactured by Moore in Birmingham) into an approximately 200 micron thick flat sheet.

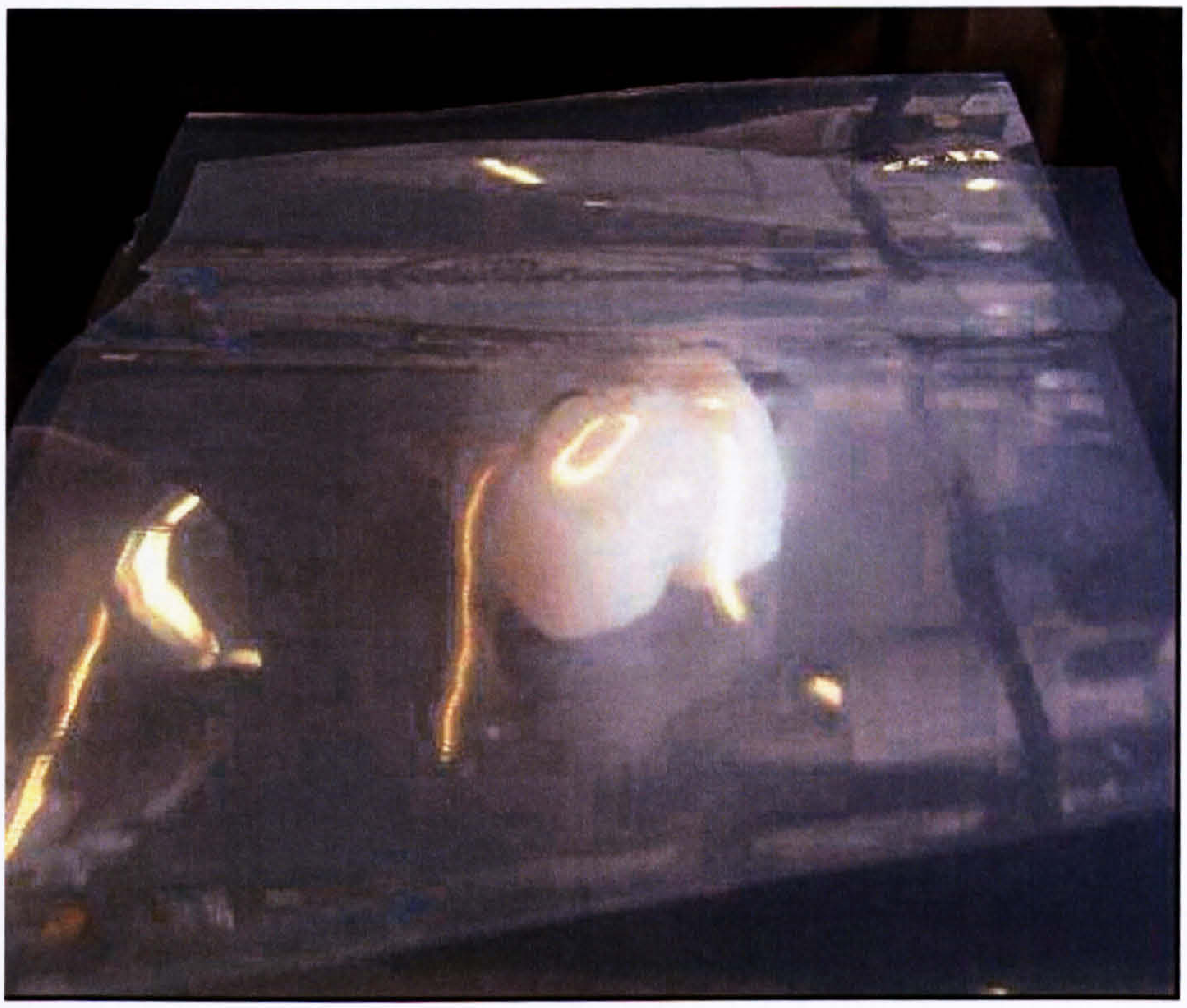

Figure 6.8: Extrudate sandwiched between two sheets of plastic.

Figure 6.9: The press used.

Two methods of drying were investigated:

1. Slow drying: The samples were placed between tissue paper and pressed to keep flat (see Figure 6.10).
2. Quick drying: The samples were vertically hung, which caused them to curl as shown in Figure 6.11.

Figure 6.10: Flat samples slowly dried using pressing techniques to keep samples flat.

Figure 6.11: A sheet sample dried using the quick drying method showing curling due to non-uniform shrinkage.

Once it was established that the slow drying technique gave the optimum result the samples were cut into the desired shape and size and were dried using this method.

Samples that had been dried flat were either used to investigate:

1. The potential for vacuum forming
2. The mechanical properties
3. The compostability

6.3.5 Mechanical Testing

The extrudate of all the blends was also collected for two minutes, in order to obtain a hand sized ball with an estimated weight of 300 grams. The ball of extrudate was pressed between two sheets of plastic and two aluminium plates. A five inch diameter ram was used to press the extrudate into a 2mm thick flat sheet to be used for impact testing.

The flat sheet was cut into samples (see dimensions below) which were then dried. Once dry, the samples were polished using P1200 glass paper on a standard polishing machine.

Samples dimensions were as follows:

Width = 5 mm (± 0.05mm)
Thickness = 5 mm (± 0.05mm)
Gauge Length = 25 mm (± 0.05mm)
Notch Depth = 1.4 mm (± 0.05mm)

Once the samples had been cut and polished they were separated into two batches. Following the ISO standard 2818 (Batch ii) samples were notched using a senior universal upright milling machine, with a vertical head set at 90 degrees and a modified mill cutter set at a 45 degree inclusive angle (see figure 6.12). An average notch length of 1.4mm was used in accordance with ISO standard 2818.

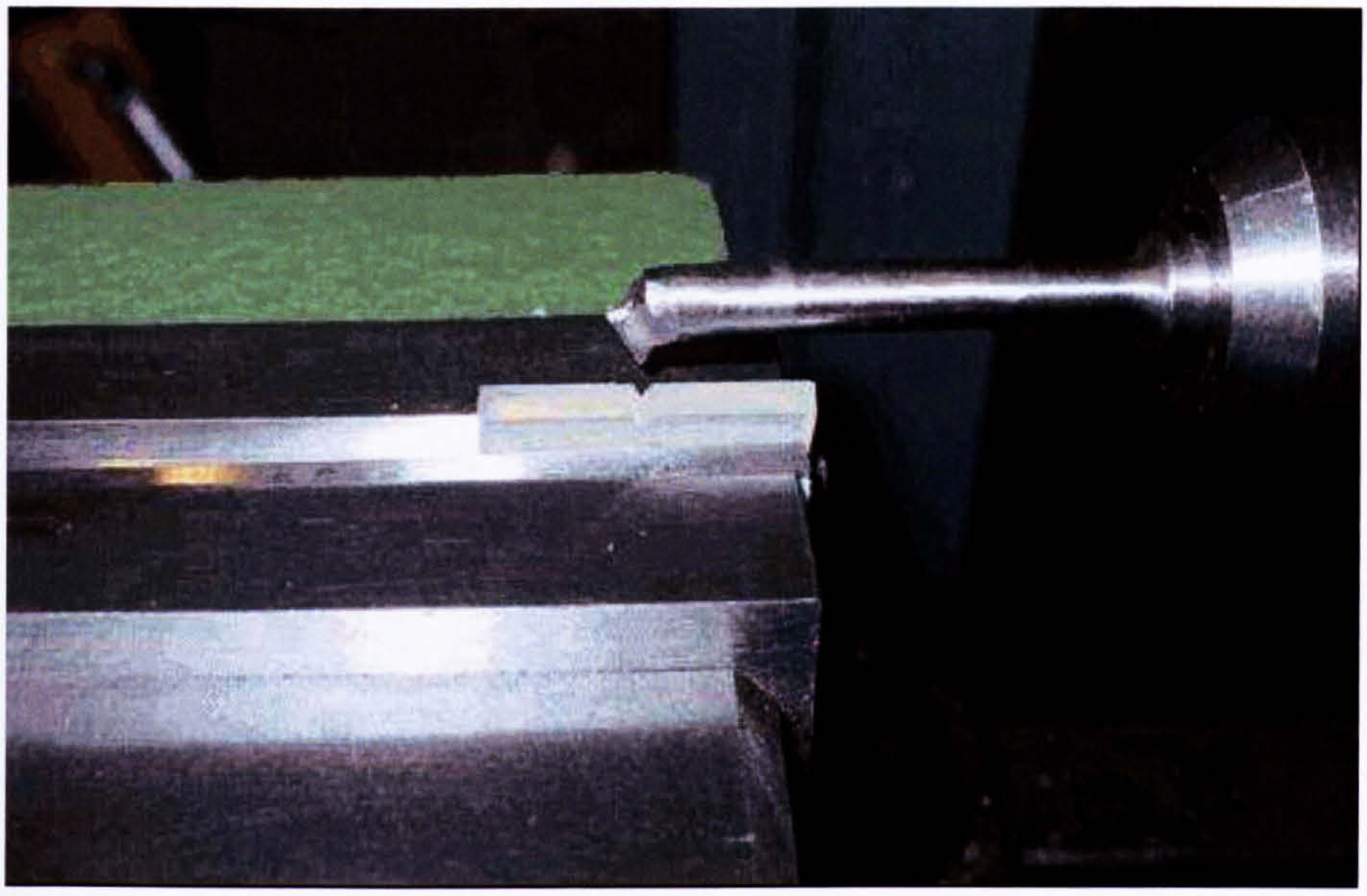

Figure 6.12: Notching (Batch ii) samples using a senior universal upright milling machine.

A Ceast impact tester (Figure 6.13) was used and set to a full-scale deflection of two Joules using a two Joules hammer and a span of 20mm. For calibration the hammer was placed to the test position and then released with no sample present. Zero joules was recorded when no sample was in place, demonstrating a correctly calibrated machine. This was compared with table 1 in the British standards "Method 359 Determination of Charpy impact strength"

Once calibration was complete the samples from (Batch ii) were placed with the notch facing away from the striking hammer. The hammer was placed back into the testing position and the needle reset manually (Figure 6.13). The safety guard was replaced and the operator, whilst wearing safety glasses, pressed the release button.

The impact energy was read and noted in Joules. Parallax is a known error when using any analogue scales with a needle, including the impact tester used (Figure 6.13) and was therefore consciously kept to a minimum. A temperature of 23°C at the time of testing was noted. The remains of the samples were collected and kept for further testing. The experiment was then repeated using the (Batch i) A samples.

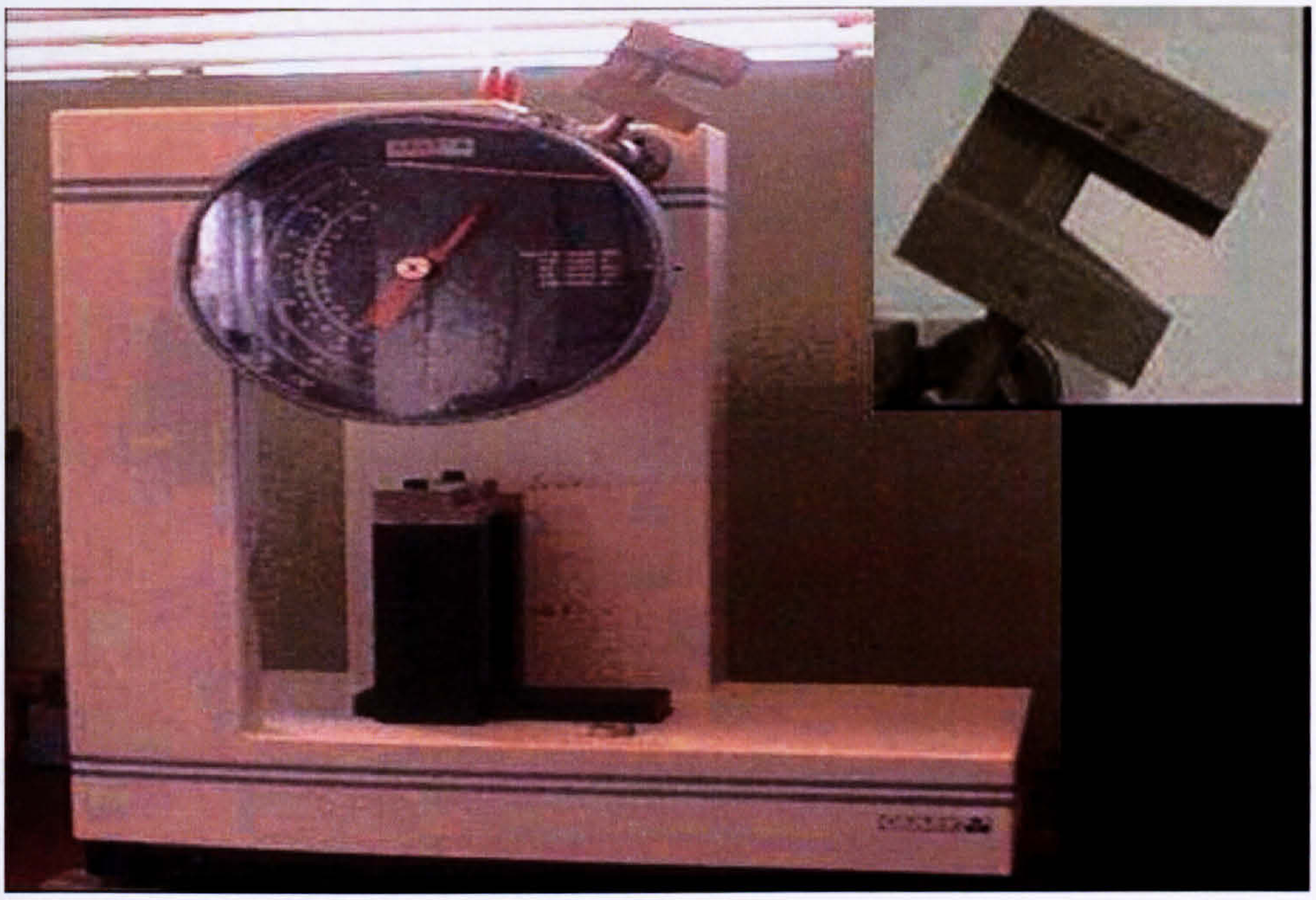

Figure 6.13: Ceest impact tester used with a two Joule hammer

The pure wheat flour samples (B) began to grow mouldy when stored in plastic sample bags. This is a problem because food hygiene standards require thermoformed trays to be placed in blue plastic bags before being boxed for transportation, as the plastic bag liner forms a hygiene barrier from possible dust and fibres from the cardboard boxes.

Initial Trial Results:

Figure 6.14: Results from first trial

Figure 6.14 shows results from first trial. Different samples have varying contents of PLA and starch, which results in a colour change and a change in diameter thickness. This was due to modifications in die swell properties.

6.3.6 Vacuum Forming

Samples A and B were tested using one of Pactiv's thermoforming tools to show whether the mechanical properties of the materials were suitable for vacuum forming. The thermoforming tool was connected to a vacuum pump. To soften the material, the sample was pressed between two sheets of plastic then placed in a sealed bag and heated in a convection oven. The softened material was extracted from the plastic sheets and was vacuum formed under different conditions (see figure 6.15 for the results).

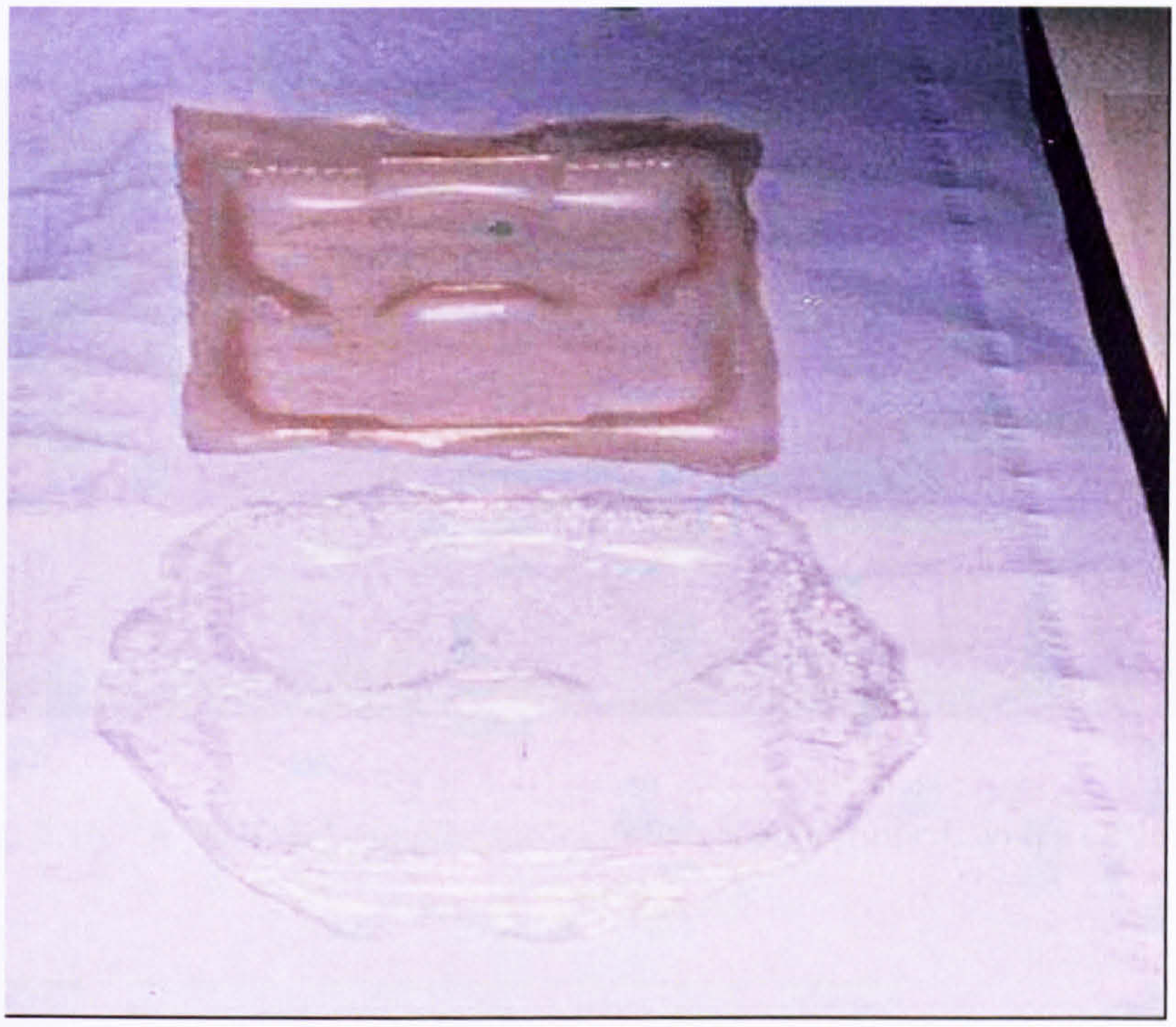

Figure 6.15: Successful vacuum forming of both A and B samples

6.4 Results and Discussion

Initial Trial Results: Figure 6.14 shows results from the first trial. Different samples have varying contents of PLA and starch, which result in a colour change and a change in diameter thickness. This was due to modifications in die swell properties.

Forming Results: The flat sheets of extrudate were successfully vacuum formed into a shape resembling that of food packaging trays (Figure 6.16). A close up of the sample "A" material demonstrates the level of detail that can be thermoformed into the material.

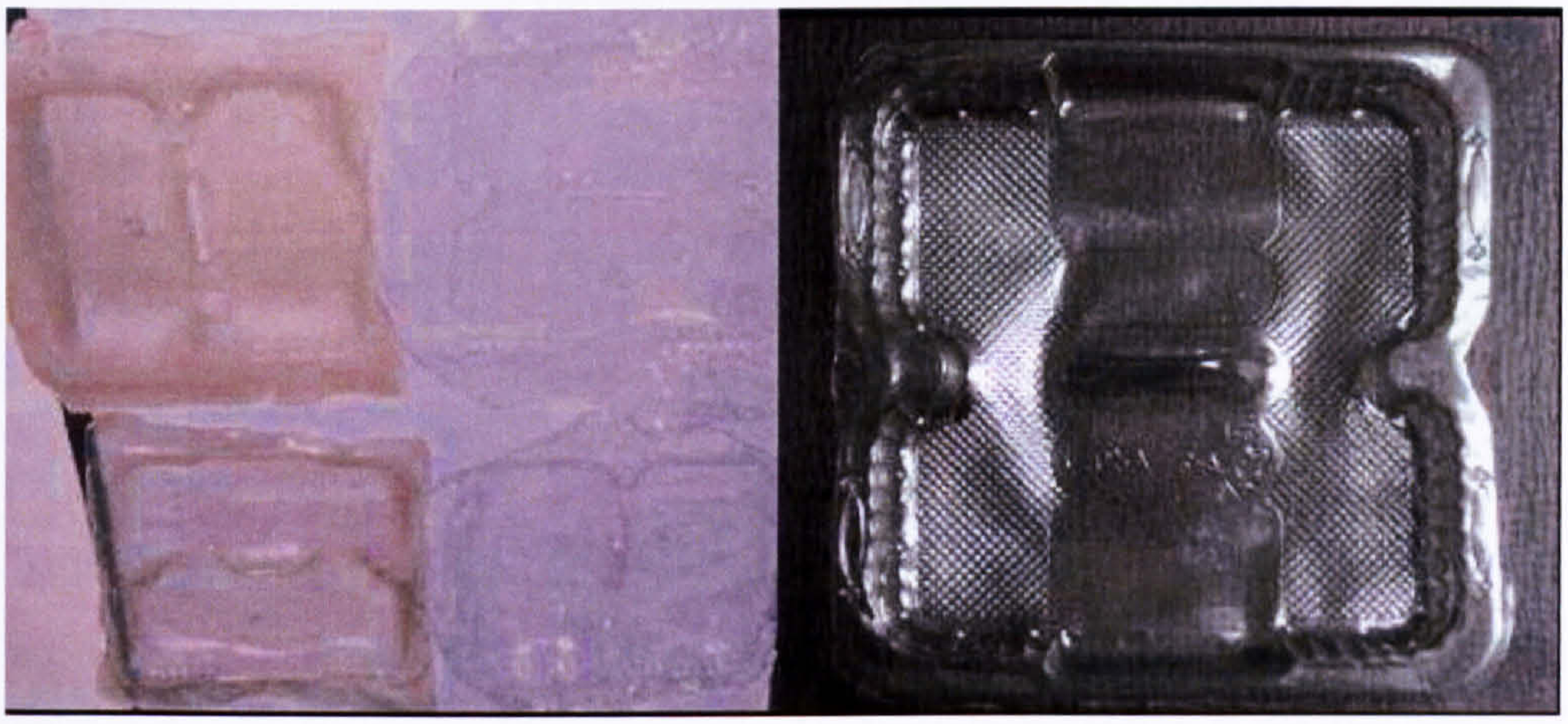

Figure 6.16: "A" and "B" samples successfully vacuum formed, with a close up of sample "A" material.

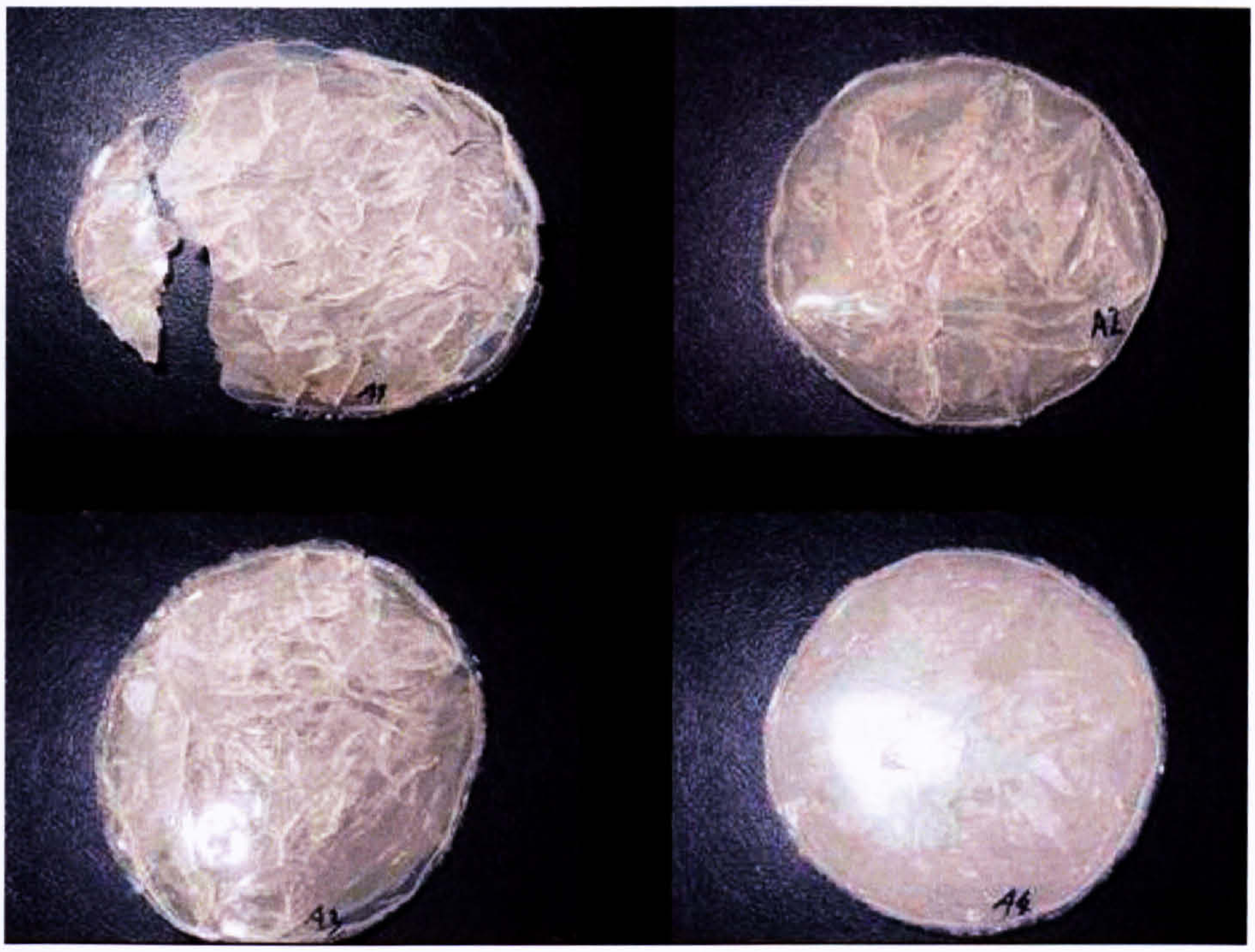

Figure 6.17: Images of extrudate intended for impact testing.

In figure 6.17, A1, A2, A3 and A4 are all purified wheat starch samples before testing, with increasing percentages of glycerol (see figure 6.1 for formulations). The images show a decrease in transparency and a decrease in crazing as the percentage of glycerol is increased. Using a standard extrusion process would avoid the 'skin' effect, which is the main cause of the crazing and weld lines.

Impact Results:

Table 6.4: Results of average impact energies from impact testing of un-notched (batch i) and notched (batch ii) samples.

	Impact Energy Absorbed (Joules) (±0.05)							
Sample	1	2	3	4	5	6	7	Av
A1 I	0.03	0.05	0.05	0.05				0.05
A2 I	0.01	0.02	0.07	0.04				0.04
A3 I	0.04	0.04	0.23	0.10	0.02	0.04		0.08
A4 I	1.33	1.69	1.81					1.61
A1 ii	0.07	0.05	0.10	0.23	0.02			0.09
A2 ii	0.01	0.02	0.01	0.02	0.09			0.03
A3 ii	0.19	0.03	0.02	0.02	0.12	0.04		0.07
A4 ii	0.08	0.05	0.02					0.05

Table 6.4 shows that the highest average result obtained was an absorbed impact energy of 1.81 Joules for A4 batch i un-notched.

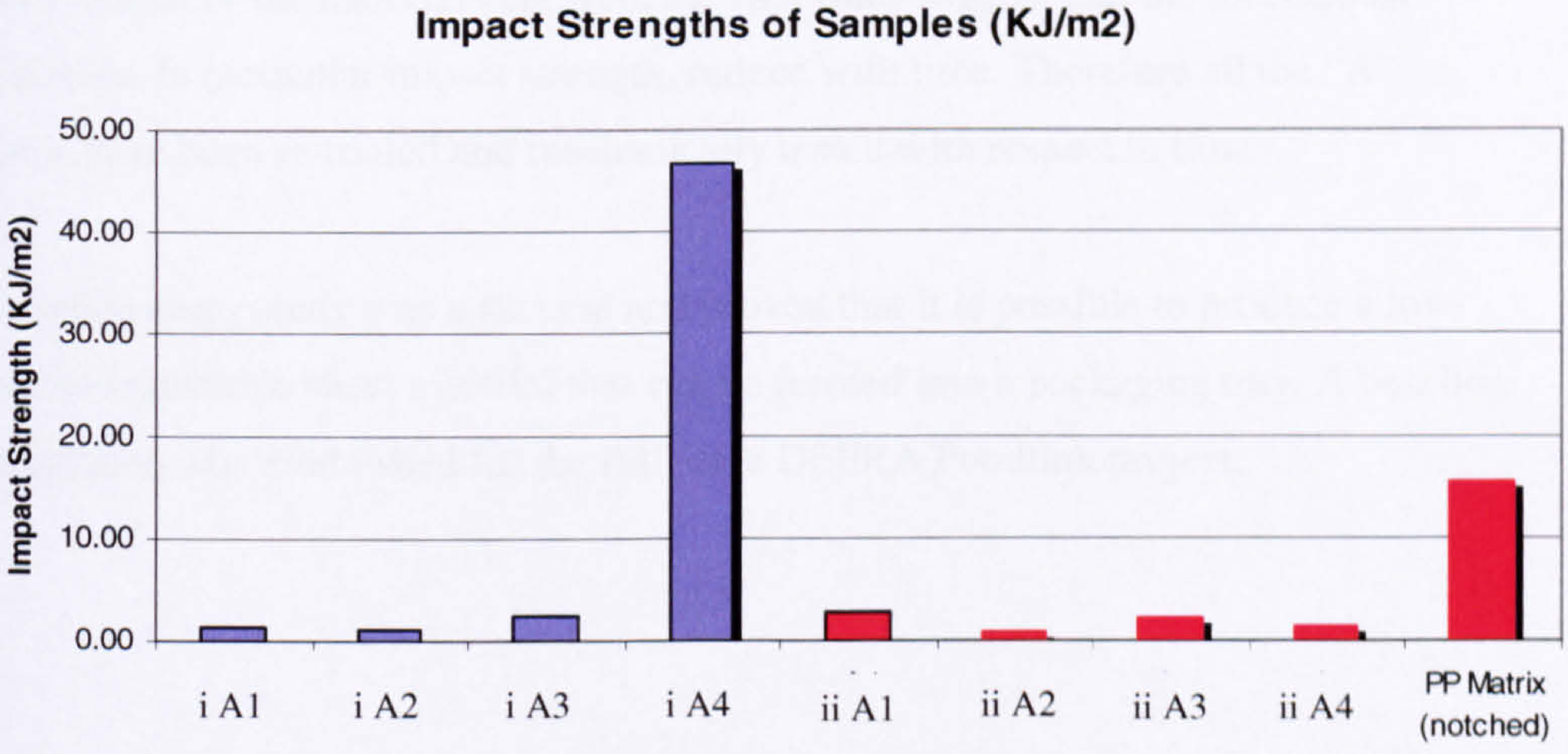

Figure 6.18: Graphic representation of average impact strength from impact testing of unnotched (batch i) and notched (batch ii) samples.

Figure 6.19 shows that the highest average result obtained was an absorbed impact energy of 46.86 KJ/m^2, for A4 (batch i) un-notched. This was compared to a previous study in which polypropylene supplied by Neste Chemicals N.V was impact tested using the same equipment under the same conditions. The results show that the impact strength of the sample A4 (un-notched, batch i) is higher than that of the polypropylene sample (notched, batch ii) 15.52KJ/m^2. However the real comparisons are the notched samples which are all significantly lower. The highest impact strength of the notched samples for example is 5.52 KJ/m^2 which is very low compared to the average impact strength of Neste Chemicals' N.V grade of polypropylene which is 15.52 KJ/m^2.

6.5 Conclusions

All samples tested to date have successfully formed an extrudate using combinations of purified wheat starch and glycerol that can be vacuum-formed into a **colourless** packaging tray.

The mechanical properties of the purified wheat starch and glycerol are lower than for conventional oil-based plastics such as polypropylene (figure 6.19).

Observations of the material kept from the first trials suggest that the mechanical properties, in particular impact strength, reduce with time. Therefore all the "A" blends have been re-trialed and mechanically tested with respect to time.

The preliminary study was a success and proved that it is possible to produce a low-cost biodegradable sheet material that can be formed into a packaging tray. A baseline formulation was established for the full scale DEFRA Foodlink project.

References

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[1] Zobel H (1988) Molecules to granules: a comprehensive starch review. Starch 40 (2), 44-50

CHAPTER 7: THE COMPARATIVE LIFE CYCLE ASSESSMENT OF BIOPOLYMERS AND OIL-BASED POLYMERS SUITABLE FOR FOOD PACKAGING

7.0 The Comparative Life Cycle Assessment of Biopolymers and Oil-based Polymers suitable for Food Packaging

Chapter seven is a comparative Life Cycle Assessment which evaluates the environmental profile of biopolymers versus oil based polymers through the supply chain, production, use and final waste disposal options. It highlights environmental 'hotspots' which need to be improved upon by industry, whilst providing organisations with valuable production, use and waste information for the materials studied. The assessment addresses the environmental groups Greenpeace's simplistic pyramid classification system.

7.1 Objective

The objective of this LCA study is to evaluate the environmental profile of biopolymers in packaging use compared to oil-based polymers through the supply chain, production, use and final waste disposal options. Data obtained from the LCA will be used to highlight any environmental hotspots which indicate areas for improvement and provide valuable information on production, use and waste.

The LCA will permit an evaluation of the simplistic pyramid classification system provided by the environmental group Greenpeace, either supporting or contesting its environmental view on polymers. The Greenpeace Pyramid of Poisonous Plastics (PPP), as shown in Fig 3.10, shows all of Pactiv's main material types (PVC, polystyrene, APET, polypropylene and polyethylene) ranked from 1 to 4, with 1 being the worst.

The Green Peace PPP ranks plastics according to their hazardous characteristics, but it doesn't take into account the full life cycle assessment. Currently Pactiv's dominant material is PVC, which Green Peace class as the most problematic plastic.
Several of Pactiv's customers have reacted to this pressure and have switched to PET instead of PVC. This is, however, a limited improvement as PET still ranks as number 3 on the pyramid.

Pactiv have recently brought out a range of products made from PLA, a commercially available biodegradable polymer. This case study aims to take into account the whole life cycle and determine whether the food packaging industry should be focusing its efforts on oil-based or non oil-based packaging.

Life cycle assessment (LCA) is a tool to evaluate the environmental burdens associated with a product, process, or activity, by identifying and quantifying energy and materials used and wastes released to the environment. It assesses the impact of those energy and material uses and releases to the environment and identifies and evaluates opportunities to effect environmental improvements. The assessment includes the entire life cycle of the product, process or activity, encompassing extracting and processing raw materials; manufacturing, transportation and distribution; use, re-use, maintenance; recycling and final disposal [1].

7.2 Goal and Scope

The goal was defined and scope set in order to firm the objectives of study and ensure that the research has a clear focus.

7.2.1 Goal

The overall goal of the LCA is to compare oil-based and non oil-based polymers based on Life Cycle Assessment and evaluate which is more environmentally sustainable for the packaging industry. The LCA is intended to provide an objective assessment of the environmental characteristics of packaging materials made from oil-based polymers such as PVC & APET and non oil-based polymers such as PLA and novel starch-based formulations produced by the RE at Brunel University as well as to evaluate the current and projected environmental impacts arising from the manufacture, use and disposal of these polymers.

The methodology for the project will be based on the ISO 14040 series of international standards for LCA. The RE's novel starch-based packaging manufactured on a lab scale at Brunel University will be benchmarked against commercially available biodegradable materials as well as oil-based packaging polymers that fulfil the same functional role.

Reasons for the LCA include:

- A contribution to knowledge regarding the environmental impacts of waste disposal of biopolymers
- Collation of additional environmental data on the waste plastic stream
- Identification of the most environmentally friendly waste disposal option for examples of both petroleum and non-petroleum based polymers.
- Assess the influence that sustainable waste management has upon the whole life cycle of the product, which will provide information to manufacturers such as Pactiv on the importance of using polymers with a lower environmental footprint and more sustainable end of life.

The target audience include manufactures such as Pactiv and suppliers of both petroleum and non-petroleum based polymers in addition to providing a contribution to knowledge.

Life Cycle Assessment (LCA) was chosen as the environmental impact assessment tool as it is the only tool currently available which can quantitatively assess the environmental impacts generated from ‘cradle to grave’.

7.2.2 Scope

The case study was based on Pactiv’s Café Revive sandwich packs, which are currently made using the oil-based plastics PVC and APET. These will be compared to biodegradable alternatives such as PLA and novel starch-based materials from Brunel University.

The information produced from the life cycle assessment will be used to:

- Inform Pactiv’s Strategic Leadership Team (STL) of the appropriate markets for biopolymers
- Contribute to a deeper understanding of the eco-profile of biopolymers

7.3 Functional Unit

1000 Café Revive Sandwich Packs at the consumers, with disposal.

Single trays weights: APET: 12.5grams
PVC: 12.5grams
PLA: 11.5grams
Novel Starch: 19.5grams

Reference Flow: Manufacture of 1040 trays, to allow for losses in the system

7.4 Systems Boundaries

The analysis is performed on a cradle-to-grave basis. This encompasses the extraction of the raw materials required for production through the manufacturing process, distribution and use, to the final disposal.

7.5 Flow Boundaries

The life phases considered were as follows:

- PVC: Extraction of petrochemicals; the production of resins; the production of additives; the 2 phase manufacturing process necessary to make food packaging trays; the process of packing and filling the trays; the retailer's role; the consumer's role and disposal options

- APET: Extraction of petrochemicals; the production of resins; production of additives; the 2 phase manufacturing process, necessary to make food packaging trays; the process of packing and filling the trays; retailer's role; consumer's role and disposal options

- PLA: The lactic acid monomer is obtained from the fermentation of sugar, which is typically obtained from co-products of food preparation. The life cycle phases considered were: growing of the corn; the starch extraction; the conversion to lactic acid; the polymerisation and PLA granulation; the production of additives; the 2 phase manufacturing process necessary to make food packaging trays; the process of packing and filling the trays; the retailer's role; the consumer's role and disposal options

- Novel Starch: The growing of the wheat; the starch extraction; the production of additives; the 2 phase manufacturing process necessary to make food packaging trays; the process of packing and filling the trays; the retailer's role; the consumer's role and disposal options

Numerous processes constitute a life cycle phase for example: the transportation of the trays from the production warehouse where the trays are stored once manufactured to the packer filler where the trays are filled with food stuff and packaged ready for the retailer and eventually the consumer, whereupon its useful life comes to an end and the tray becomes waste.

The following five waste scenarios were considered and matched to the most suitable waste disposal route [2] for the sample materials:

1. UK MSW (estimated as 89% landfill, 11% incineration with energy recovery, for this project)

   The materials suitable for this disposal option include:
   a. APET
   b. PVC
   c. PLA
   d. Novel Starch

2. Proposed 2020 MSW (35% landfill, 11% incineration, with energy recovery, 54% centralised composting) [3]

   The materials suitable for this disposal option include:
    a. APET
    b. PVC
    c. PLA
    d. Novel Starch

3. Municipal Composting

   The materials suitable for this disposal option include:
    a. PLA
    b. Novel Starch
4. Domestic Composting (Efficient management)

   The materials suitable for this disposal option include:
    a. Novel Starch

5. Domestic Composting (Poor quality management)

   The materials suitable for this disposal option include:
    a. Novel Starch

A Life Cycle Assessment comparison of all five waste disposal scenarios will identify the best waste disposal option, which generates the fewest environmental impacts for Novel starch and PLA.

APET and PVC however are only suited for option 1 and 2, and a LCA comparison of these, plus the PLA and novel starch will determine whether the packaging industry should be concentrating their efforts on non-crop based polymers or petroleum-based polymers given the current MSW and that proposed for 2020.

7.6 Inventory Analysis

The inventory phase is where the environmental interventions associated with the life cycle for the functional unit are collected, quantified and collated. In this case study, these are the material and energy inputs and product and emission outputs to air, water and land. A boundary is drawn around the system under analysis and the inputs and outputs, which cross the boundary are quantified.

7.6.1 Data Collection

Data quality should be stated in any LCA in order for the reviewers and potential users to assess the validity and suitability of data for specific purposes.

7.6.2 Temporal Coverage

Wherever possible, data should be representative of current conditions, however, when using some databases, data is often not updated and could be in excess of 15 years out of date. Therefore, dates will be recorded when possible.

7.6.3 Geographical Coverage

PLA production currently takes place in the US whereas the production of all the other polymers under review is based in Europe. Therefore larger distances have been recorded for PLA.

7.6.4 Technological Coverage

The technology considered in this project will be that used by Pactiv, its suppliers and its customers. However, this is typical of the food packaging industry as a whole given that it is a well developed industry.

7.6.5 Precision of Data

Wherever possible, exact data from industry has been used. Where this was not possible data has been taken from datasets or representatives have been used. These secondary sources of information will often be average values.

7.6.6 Completeness of data

It is not practically possible to account for every flow in the life cycle. There are diminishing returns in the search for detail. The emphasis of the project is on fully describing all the primary flows and quantifying all the secondary flows. When commercial sensitivity prevents one flow being explicitly described, it will be included in the analysis as a black box with its corresponding inputs and outputs.

7.6.7 Sources of data

Sources of data are fully acknowledged and referenced. In the case of generic data, the database used will be reported and a general description of the data origins will also be provided.

7.6.8 Uncertainty within data

Uncertainties in process variability will be noted whenever variation is unpredictable.

7.6.9 Data Gaps

Data gaps in an LCA are unavoidable and therefore any such gaps will be identified and explained.

7.6.10 Data Sources

Primary data for the study was obtained directly from the relevant industries and the research team involved, whilst secondary data was obtained from generic sources and databases such as literature and SimaPro databases, for which the quality of data will be clearly stated in relation to its temporal, geographical, and technological coverage, as well as its precision, completeness and the reporting of any uncertainties.

7.7 Inventory Input Data – Raw Materials

PVC and APET have a petroleum-based feedstock, whereas both PLA and the RE's novel starch are based on an agricultural feedstock and therefore require little or no fossil-based components. However, raw material extraction, processing and energy production do require the use of fossil fuels.

PVC and APET manufacture are well-established processes. Therefore where primary information could not be obtained directly from Pactiv as well as Pactiv's suppliers and customers, Sima Pro databases have been used. Information for PLA has been obtained from trials carried out by the RE at Pactiv's main manufacturing site in Newcastle, or from Cargill Dow. Novel starch was manufactured by the RE on a laboratory scale and as such little information is available on a full manufacturing scale. Therefore substitutes and expert opinions have been used.

Table 7.1 Material inputs for production of: APET, PVC, PLA & Novel Starch

Raw Material	Consumption (kg/Functional Unit)	Original Data Source(s)
Virgin APET	**12.5 g**	**Pactiv UK Eco Invent 2001**
APET internal REWORK	**5.0g**	**Pactiv UK**
APET external REWORK	**1.25g**	**Pactiv UK**
Masterbatch additives	**0.0125g**	**Pactiv UK IDEMAT 2001**
Additives	**0g**	**Pactiv UK ETH-ESU 96**

(Consumption measured in g of material for 1000 Café Revive Sandwich Packs at the consumers, with disposal. (APET = 12.5grams) (Manufacture of 1040 trays, to allow for losses in the system)

Raw Material	Consumption (kg/Functional Unit)	Original Data Source(s)
Virgin PVC	**12.5 g**	**Pactiv UK Eco Invent 2001**
PVC internal REWORK	**6.25g**	**Pactiv UK**
Masterbatch additives	**0.0125g**	**Pactiv UK IDEMAT 2001**

(Consumption measured in g of material for 1000 Café Revive Sandwich Packs at the consumers, with disposal. (PVC = 12.5grams) (Manufacture of 1040 trays, to allow for losses in the system)

Raw Material	Consumption (kg/Functional Unit)	Original Data Source(s)
Virgin PLA	11.5 g	Pactiv UK
PLA internal REWORK	4.6g	Pactiv UK
PLA external REWORK	1.15g	Pactiv UK
Masterbatch additives	0.0125g	Pactiv UK IDEMAT 2001
Additives	0g	Pactiv UK ETH-ESU 96

(Consumption measured in g of material for 1000 Café Revive Sandwich Packs at the consumers, with disposal. (PLA = 11.5grams) (Manufacture of 1040 trays, to allow for losses in the system)

Raw Material	Consumption (kg/Functional Unit)	Original Data Source(s)
Virgin Novel Starch	19.5 g	Brunel University
Novel Starch internal REWORK	7.8g	Pactiv UK Brunel University
Novel Starch external REWORK	1.95g	Pactiv UK Brunel University
Masterbatch additives	0.0125g	Pactiv UK IDEMAT 2001
Additives	0g	Pactiv UK ETH-ESU 96

(Consumption measured in g of material for 1000 Café Revive Sandwich Packs at the consumers, with disposal. (Novel Starch = 19.5grams) (Manufacture of 1040 trays, to allow for losses in the system)

7.8 Impact Assessment Interpretation

Sima Pro 6.0 LCA software was used to manage the data, as it is currently the most widely used in LCA studies such as this. The main Impact Assessment method used was Eco-Indicators 1999, which includes the following impact categories:

- Carcinogens creation: A carcinogen is any substance that promotes cancer. This can occur by altering cellular metabolism or by damaging DNA cells, both of which affect normal biological process in the human body. Carcinogens are classified in the following way:
    1. Human Carcinogen: Exposure to this type of carcinogen is harmful to humans
    2. Probable Human Carcinogen: Exposure to this type of carcinogen is probably harmful to humans
    3. Possible Human Carcinogen: Exposure to this type of carcinogen is possibly harmful to humans
    4. Not classifiable as to Human Carcinogenicity: Exposure to this type of carcinogen is not classifiable to humans.
    5. Evidence of Non-Carcinogenicity for Humans: Exposure to this type of carcinogen is probably not harmful to humans
- Climate change potential and depletion of the ozone layer: Increasing amounts of greenhouse gases such as carbon dioxide and methane enhance the greenhouse effect and lead to an increase in global temperature. Climate change is often therefore referred to as 'global warming'. Since the effects may also include storms or regional cooling, the term 'climate change' is more suitable. The natural greenhouse effect is an important factor in heating the atmosphere: short wavelength solar radiation entering the Earth's atmosphere is re-radiated from the Earth's surface in longer infrared wavelengths, and then reabsorbed by components of the atmosphere. Without the natural greenhouse effect the average global temperature would be about -18°C. Due to the greenhouse effect the average global temperature is 15°C.
- Eco-toxicity: Is concerned with impacts on all species and has therefore an additional layer of complexity compared to the category human toxicity which considers just one species, for example: Homo sapiens.

- Acidification: This refers to acid precipitation from the atmosphere, whether in the form of dry fall, finely divided acidic salts, rain or snow. Naturally occurring carbonic acid normally makes rain and snow mildly acidic, approximately pH 5.6. However, human activities often result in much stronger and more damaging acids. Sulphur oxides and nitrogen oxides are mainly released from the combustion of fossil fuels and form sulphuric and nitric acids respectively. Damage is caused to building materials, human health, crops and natural ecosystems.
- Eutrophication: Occurs when there is an increase in the concentration of nutrients in a body of water or soil, occurring naturally and as a result of human activity. It may be caused by the run-off of synthetic fertilisers from agricultural land, or by the input of sewage or animal waste. It leads to a reduction in species diversity as well as changes in species composition, often accompanied by massive growth of dominant species. In addition, the increased production of dead biomass may lead to depletion of oxygen in the water or soil since its degradation consumes oxygen. This contributes to changes in species composition and death of organisms.
- Land use: This category covers several consequences of human land use. A distinction can be made between the resource aspect, land competition, biodiversity, and the loss of life support functions (Guinee, 2002)
- Minerals are natural compounds formed through geological processes. In order to be classified as a mineral a substance must be a solid and have a crystalline structure. It must also be inorganic, naturally occurring, homogenous substance with a defined chemical composition.
- Fossil fuel depletion: Fossil fuels are hydrocarbons formed from the remains of dead plants and animals. The utilization of fossil fuels has enabled large-scale industrial development. However, fossil fuels are a non-renewable resource and concerns as to when they will run out are rising. Predicting the depletion is an issue of accuracy of resources, especially for oil, whose known reserve is the smallest in terms of years.

For this LCA the Land use and Radiation categories have been taken out due to their being controversial.

The damage-orientated methodology was selected because it meets the requirements of the international standard ISO 14042, is compatible with Sima Pro6.0 and has been used in a number of other Biopolymer LCA studies. Eco Indicators 99 allows the option to present results as classified scores, normalised scores and to undertake a weighting process to derive 'single scores'. All approaches have been used to guide interpretation of the results, with Heirarchist / average perspective used when weighting

A sensitivity analysis of the Eco-Indictor results was carried out to conclude whether the methodology used influenced the results. The CML 2 baseline 2000 methodology was used for this comparison, which includes the following impact categories:

- Abiotic depletion: Abiotic resources are regarded as non-living, e.g. iron ore, wind energy, coal and oil. Most abiotic resources are non-renewable resources, which have built up or evolved over a geographical time-span and cannot be replaced except on a similar time-scale, e.g. coal; oil and copper. There are exceptions to this, for example, wind. The extraction of abiotic resources should therefore be considered to ensure a sufficient supply in the future.

- Global warming: Refers to the impact of emissions on the atmosphere radiation heat absorption, also known as green house effect. Emissions are characterised as the global warming potential for a 100 year period. The units used are kg per CO_2.

- Ozone layer depletion: Refers to the deterioration of the ozone layer that stops solar UV-B radiation from entering the atmosphere. Units used are kg per CFC–11.

- Human toxicity: Substances considered to be toxic to humans are assessed in this category. It includes substances that have both chronic effects, for example, longer-term, slower acting substances, and acute effects, for example, shorter-term, faster acting substances.

- Eco-toxicity is divided into three categories depending upon the environmental sub compartment:
    - Fresh water aquatic eco-toxicity
    - Marine aquatic eco-toxicity
    - Terrestrial eco-toxicity

- Photochemical oxidation: Also known as photo–oxidant formation. Sunlight causes some emissions like VOC's and CO in the presence of NOx to form chemical oxidising compounds such as ozone. Photo-oxidant formation is also known as summer smog. Characterisation results are expressed in "kg ethylene equivalent".

- Acidification: see above.

- Eutrophication: See above

As discussed in Chapter 8 and Davies *et al.*, (2006), not all the polymers are suitable for all disposal scenarios. However all are suitable for disposal in the current MSW scenario.

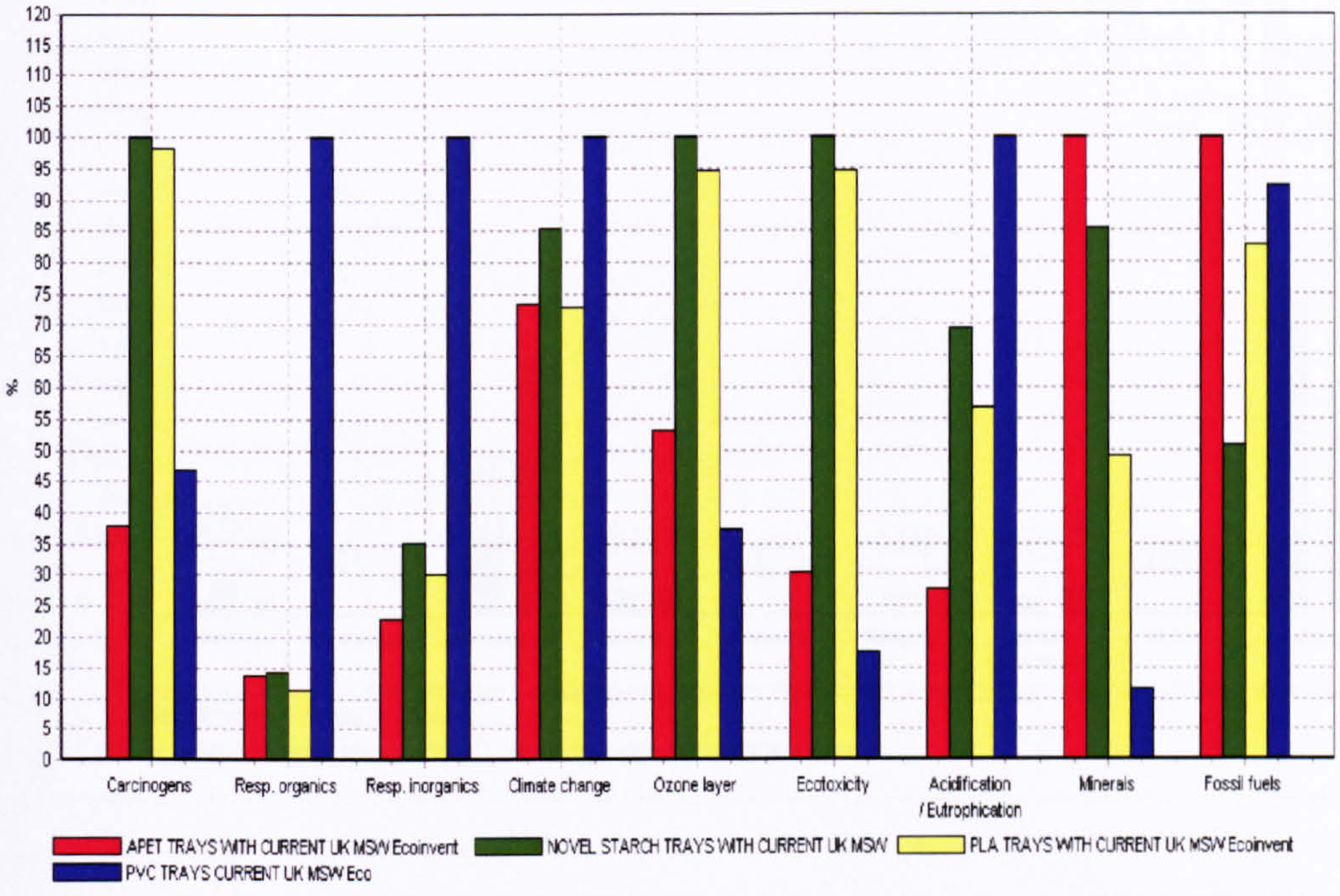
The impact assessment methodologies enable the LCA data to be categorised, classified, normalised and, in Eco indicators, weighted within individual impact categories.

7.9 Results: Impact Assessment and Interpretation – Eco Indicators 99 Methodology

The results of the impact assessment with Eco Indicators 99 Methodology (without Land Use and Radiation) are presented and interpreted below. The 'Base Case' of all polymers, evaluated with the default set of impact categories for current UK MSW disposal is considered first.

7.9.1 Assessment with UK Current MSW – the base case

The results for the base case assessment for the characterised scores are given below in Figure 7.1



Comparing product stages; Method: Eco-indicator 99 (H) V2.1 No Land Use, Radiation / Europe EI 99 H/A / characterization

Figure7.1: Characterised scores for all polymers disposed by Current UK MSW (EI99)

In all cases the conversion from the raw state of the material into a granulate format suitable for use in the extrusion process contributed the most environmentally damaging effect. The results show that in terms of fossil fuels novel starch is by far the least environmentally damaging material and APET the most damaging. PVC scores better than APET in this category - due its chlorine content it uses less fossil fuels. However, this chlorine content also causes very high scores when looking at the impact on climate change, respiratory organics and respiratory in-organics.

The results for the base case assessment for the normalised scores are given below in Figure 7.2

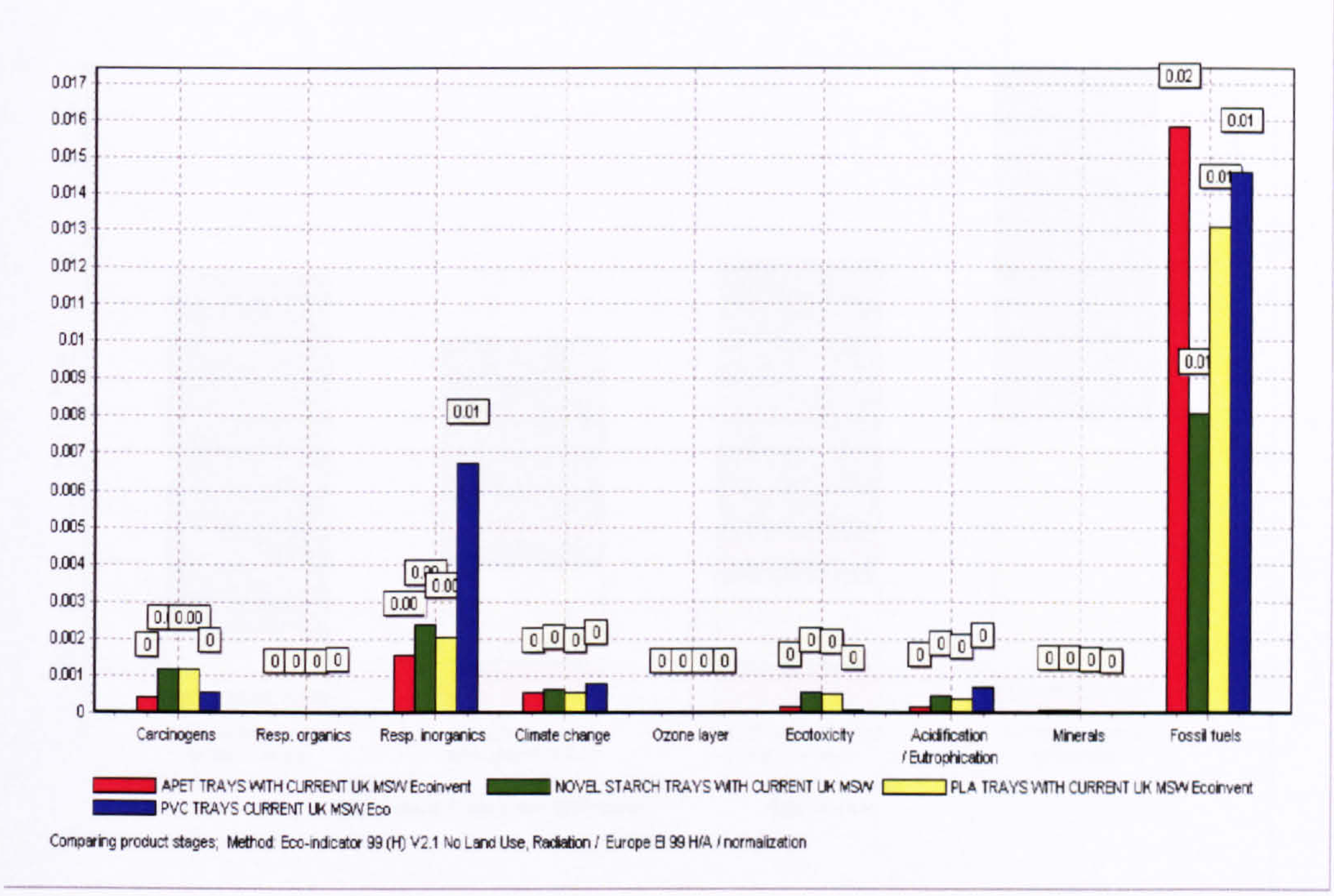


Figure 7.2 Normalised scores for all polymers disposed by Current UK MSW (EI99)

The results show that fossil fuel consumption and respiratory in-organics are the most significant categories of environmental impact. Novel starch has the lowest fossil fuel consumption because no feedstock is consumed in manufacturing the polymer. PLA has a similar manufacturing process to Novel starch, but uses more energy in production so the net result is higher fossil fuel consumption. PVC is significantly worse than other materials in the respiratory in-organics category due to the effects of the granulation stage of polymer production.

The results for the base case assessment normalised and weighted to a 'single' score as EI99 Ecopoints (Pt) are given below in Figure 7.3

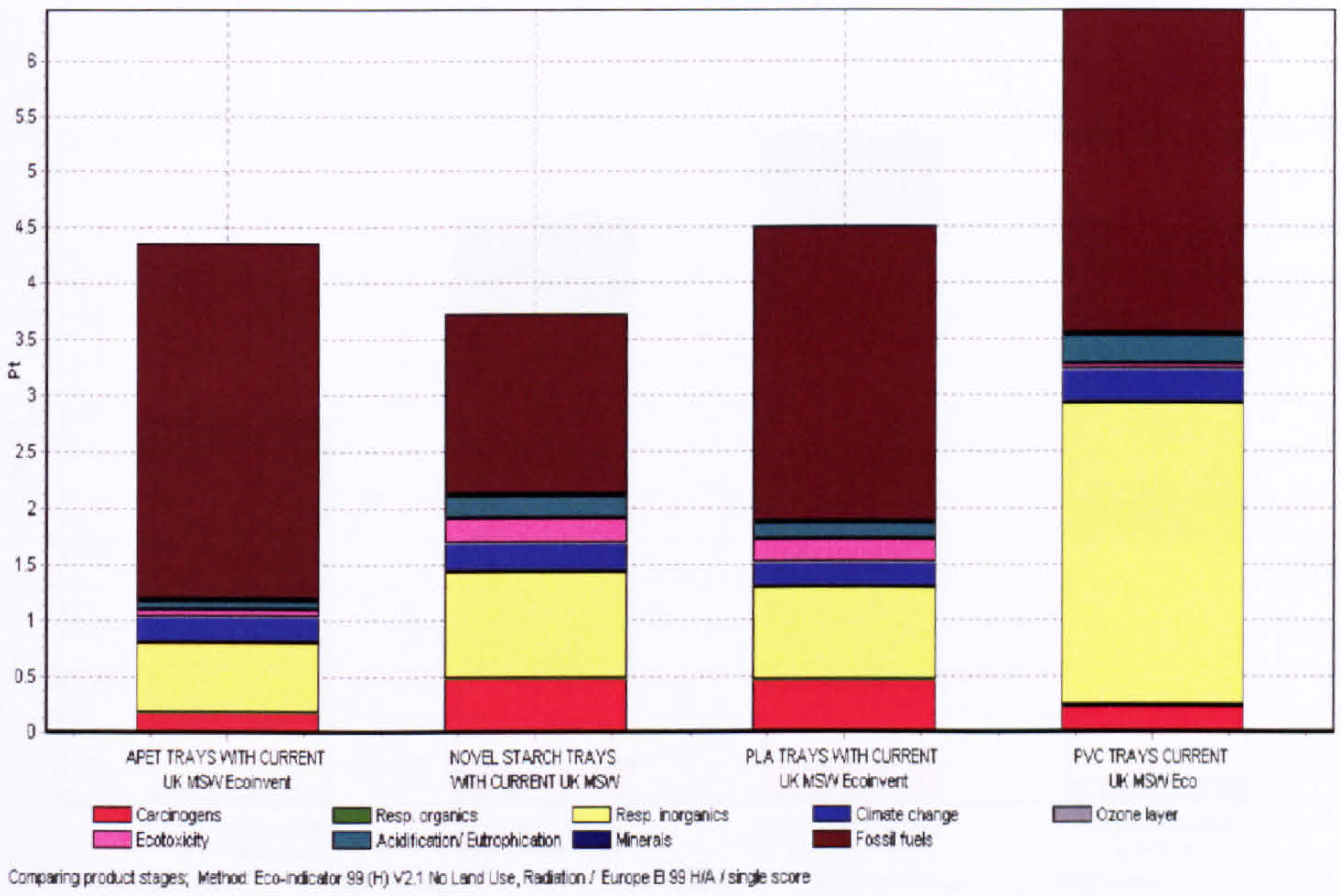
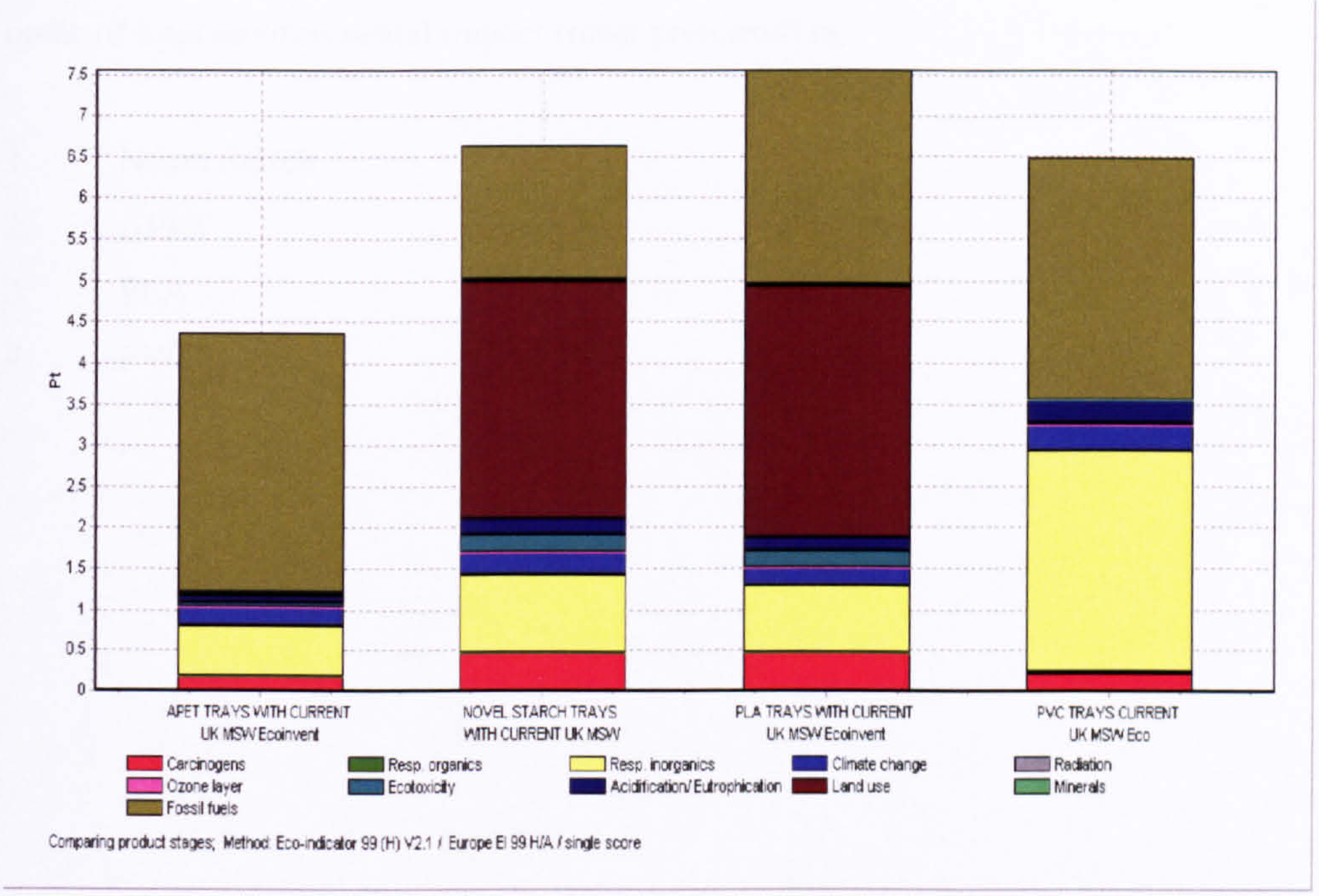


Figure 7.3: Comparison of all tray materials with UK current MSW disposal – single score values from weighting (Eco Indictor 99 method).

Figure 7.3 shows that novel starch is the least environmentally damaging, suggesting that the use of the novel starch biopolymer has environmental benefits in terms of waste management options. PVC has the highest impact due to high emissions of respiratory inorganics (from the PVC granulate production) and high consumption of fossil fuels for feedstock and polymer production. Despite APET having the largest demand for fossil fuels it scores relatively low in the other impact categories. There was little difference between the four polymers in greenhouse gas emissions contribution to Climate Change.

Land Use is included in a number of LCA studies and is available within the EI99 methodology. As stated earlier, this was not one of the impact categories selected as a default in the EI impact assessment methodology used here. However, for comparison purposes Figure 7.4 presents the same data as in Figure 7.3, including Land Use and Radiation categories within the assessment.



Comparing product stages; Method: Eco-indicator 99 (H) V2.1 / Europe EI 99 H/A / single score

Figure 7.4: Comparison of all tray materials with UK current MSW disposal – single score values from weighting (EI99 method).

The inclusion of Land Use changes the ranking of the novel starch and the PLA polymers. The results show that with the inclusion of land use and radiation categories PLA and Novel Starch are now the least preferred options. The Land use impact category brings in the land requirement for the agricultural production of wheat for starch (maize starch was used as a surrogate). However, its effect on the rankings of the polymer is not a complete reflection of its role in the analysis. The inclusion of Land Use in LCA is controversial and when included, weighting categories and the interpretation phase are by no means clear. For example, the present production of starch feedstock for the biopolymers is derived from agricultural land under 'permanent' cultivation. It is also unlikely that any change in demand for biopolymers will affect this area of land to any significant extent.

For the purposes of this study, therefore, it is considered best to exclude Land Use and compare the polymers on a 'fairer' basis. The conclusions will need to recognise that this exclusion influences the outcome.

Overall, in the absence of the land use and radiation categories the polymers rank in order of least environmental impact (most preferred) as:

1. Novel Starch
2. APET
3. PLA
4. PVC

7.9.2 Assessment with UK 2020 waste disposal scenario and composting scenarios

The base case analysis was extended to evaluate the likely effects of the proposed waste management scenario for the UK in 2020. In this scenario the percentage of landfill has been reduced in line with a report written by the government's strategy unit titled 'Waste not, Want not' in which the government sets new targets to reduce landfill and increase percentages of incineration with energy recovery.

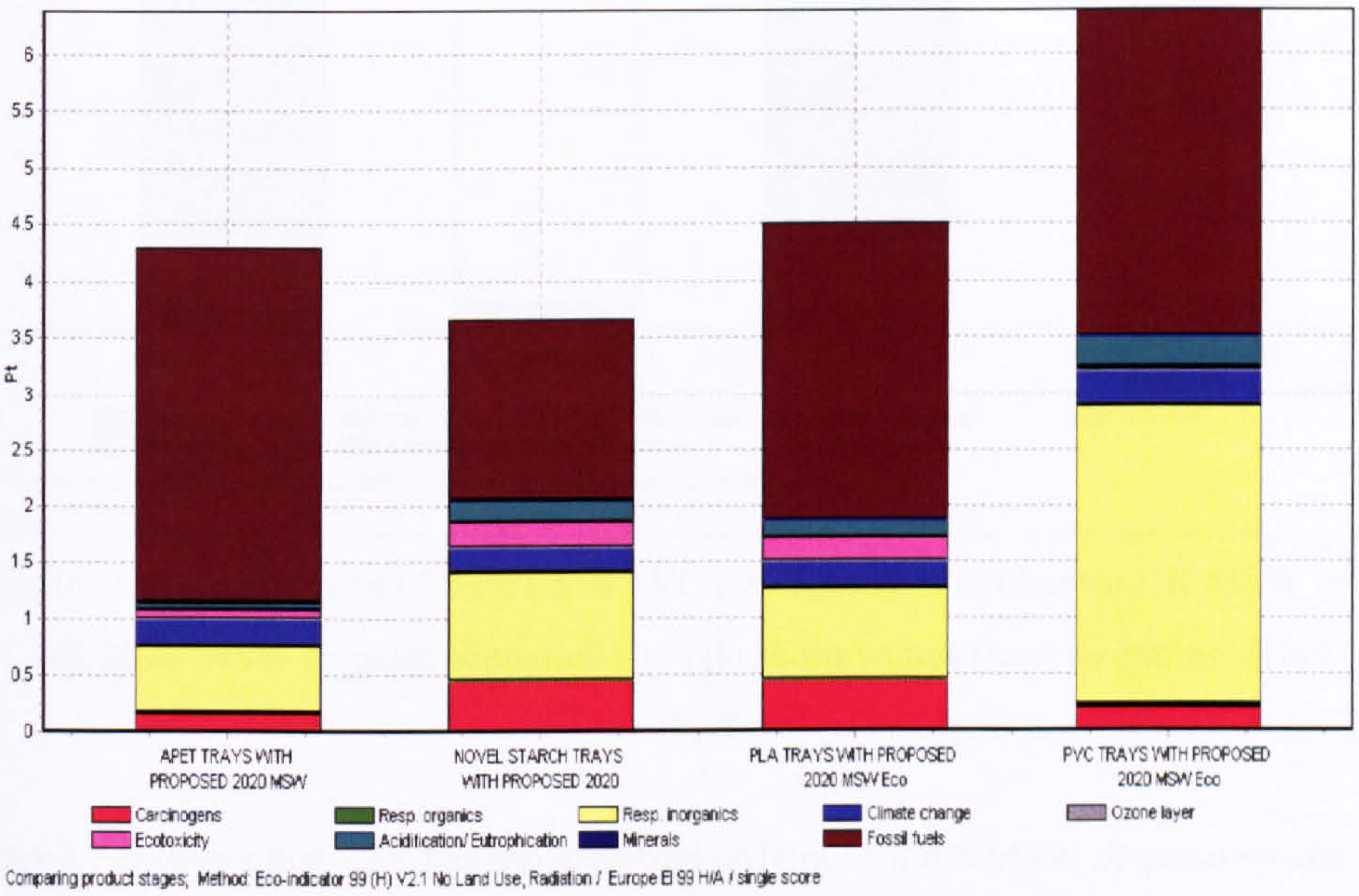
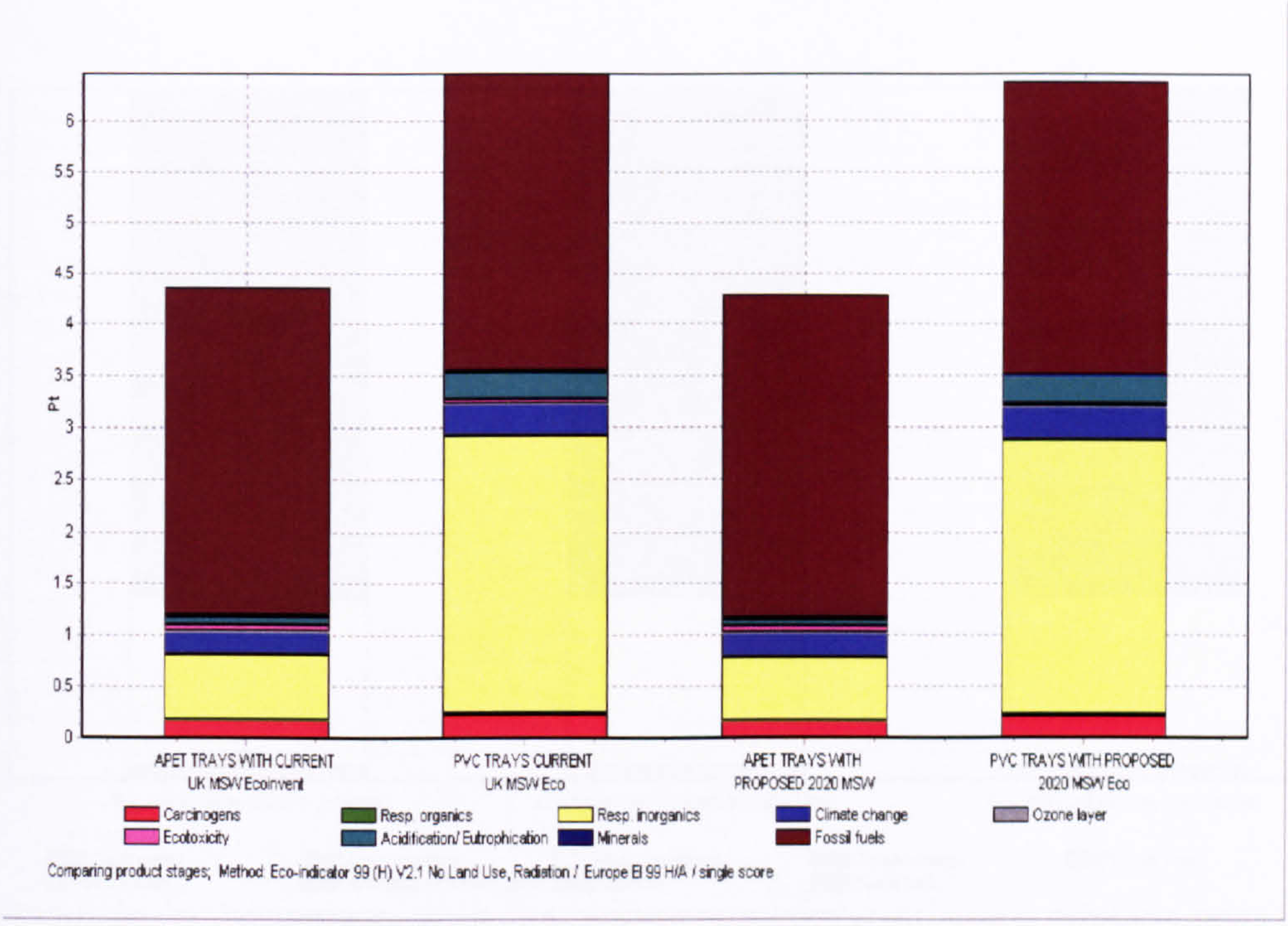


Figure 7.5: Comparison of all tray materials with UK 2020 MSW disposal scenario – single score values from weighting (EI99 method).

The results show that when comparing the current MSW (Figure 7.3) with the proposed 2020 (Figure 7.5) there is little difference from the current MSW and no change to the ranking of the polymers.

To further clarify this, a graph showing the best disposal options for APET and PVC is shown in Figure 7.6.



Comparing product stages; Method: Eco-indicator 99 (H) V2.1 No Land Use, Radiation / Europe EI 99 H/A / single score

Figure 7.6: Comparison of APET and PVC tray materials in Current UK MSW and UK 2020 MSW disposal scenarios – single score values from weighting (EI99 method).

Figure 7.6 shows that APET is the preferred polymer for the MSW disposal stream both now and in the future. The other two disposal options, municipal composting and home composting are not suitable for petroleum-based polymers and so are not evaluated as a viable waste management option.

The preferred disposal option for PLA was investigated.

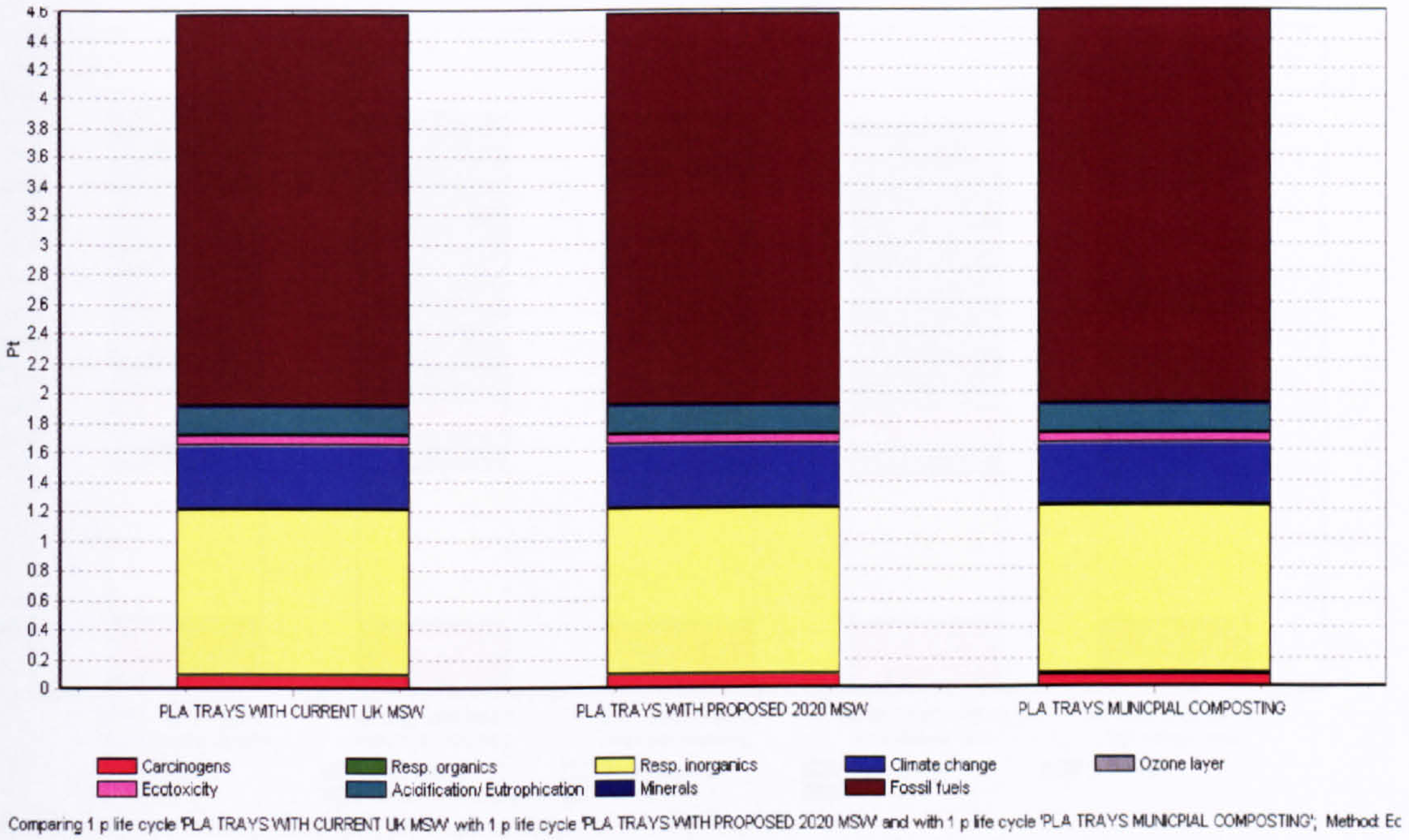


Figure 7.7: Preferred waste disposal option for PLA – single score values from weighting (EI99 method).

Work carried out in chapter 8 and in the paper in appendix B concludes that despite PLA being a biodegradable polymer it will only biodegrade under high temperature industrial composting conditions. Therefore home composting has not been considered as a viable waste management option in this LCA. The results (Figure 7.7) show that there is a remarkable similarity in all the viable waste disposal scenarios. However, it is clear that the 2020 waste management scenario yields little reduction in terms of environmental impact compared with current MSW, which is heavily reliant on landfill. This further suggests the need for a material which readily breaks down under low temperature home composting conditions.

The preferred disposal option for Novel Starch according to Sima Pro is low methane home composting. Novel starch is the only material which is appropriate for the full range of waste management options.

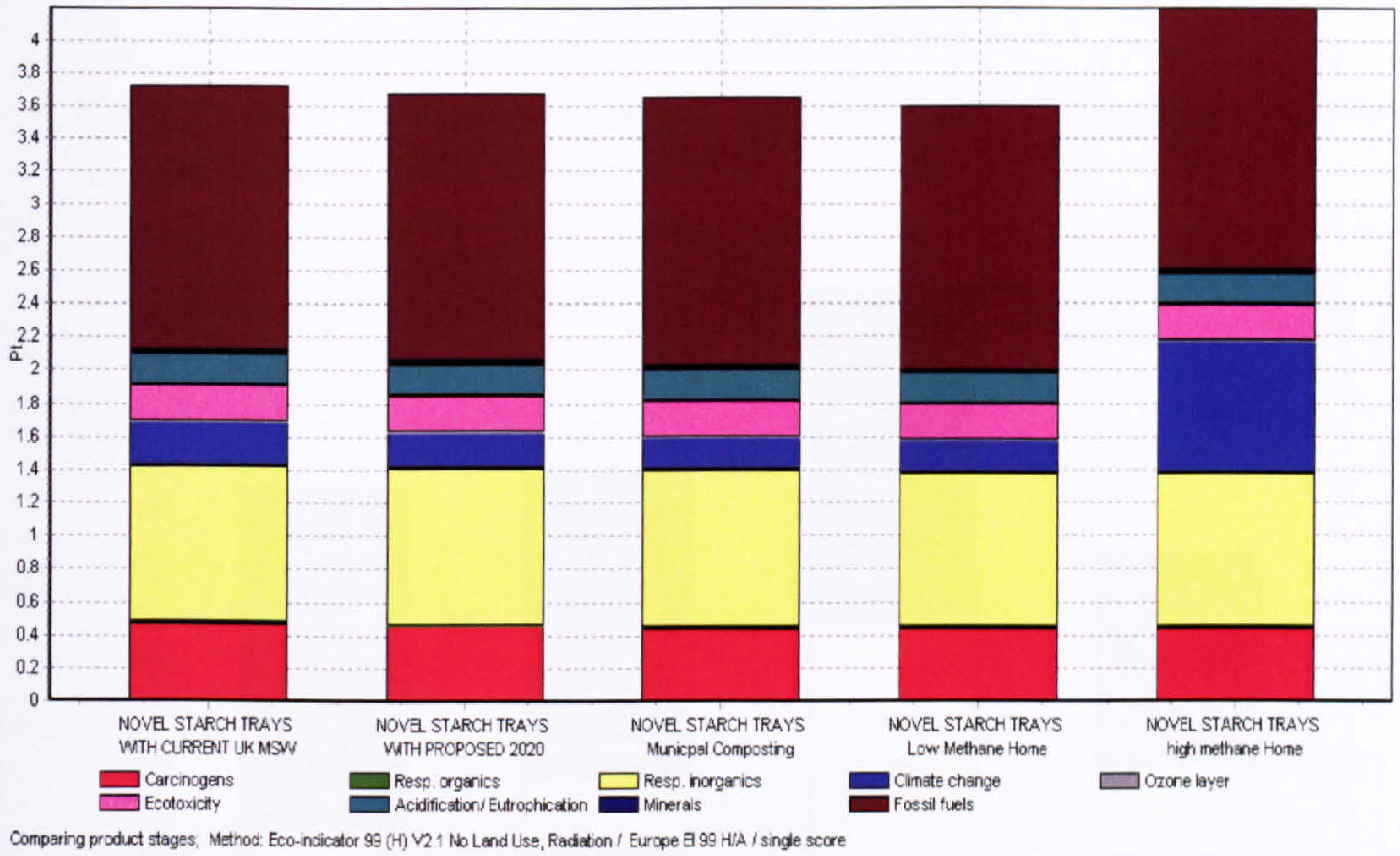


Figure 7.8: Preferred waste disposal option for Novel Starch – single score values from weighting (EI99 method).

Previous comparisons did not include home composting systems because the materials under consideration were not suitable for this disposal method. Since Novel starch can be disposed of in this manner home composting is considered as an option. It is clear that home composting offers both the lowest impact disposal system and, depending upon the assumptions about fugitive methane emissions, the worst disposal option. The high methane scenario is a very much worst case and it is likely that most home composting systems will be operated in the low methane mode.

The results show home composting with low methane production is the optimum environmental waste disposal option for the novel starch waste stream and home composting with high levels of methane production is the least preferred environmental option. It is interesting to note that there is very little difference

between four of the waste disposal options: current MSW, proposed 2020 MSW, municipal composting and home composting with low methane production.
Further analysis of the graph shows that the biggest impact to the environment is the fossil fuel usage.

Figure 7.9 shows the data for each polymer with their optimum disposal scenario from the ones examined.

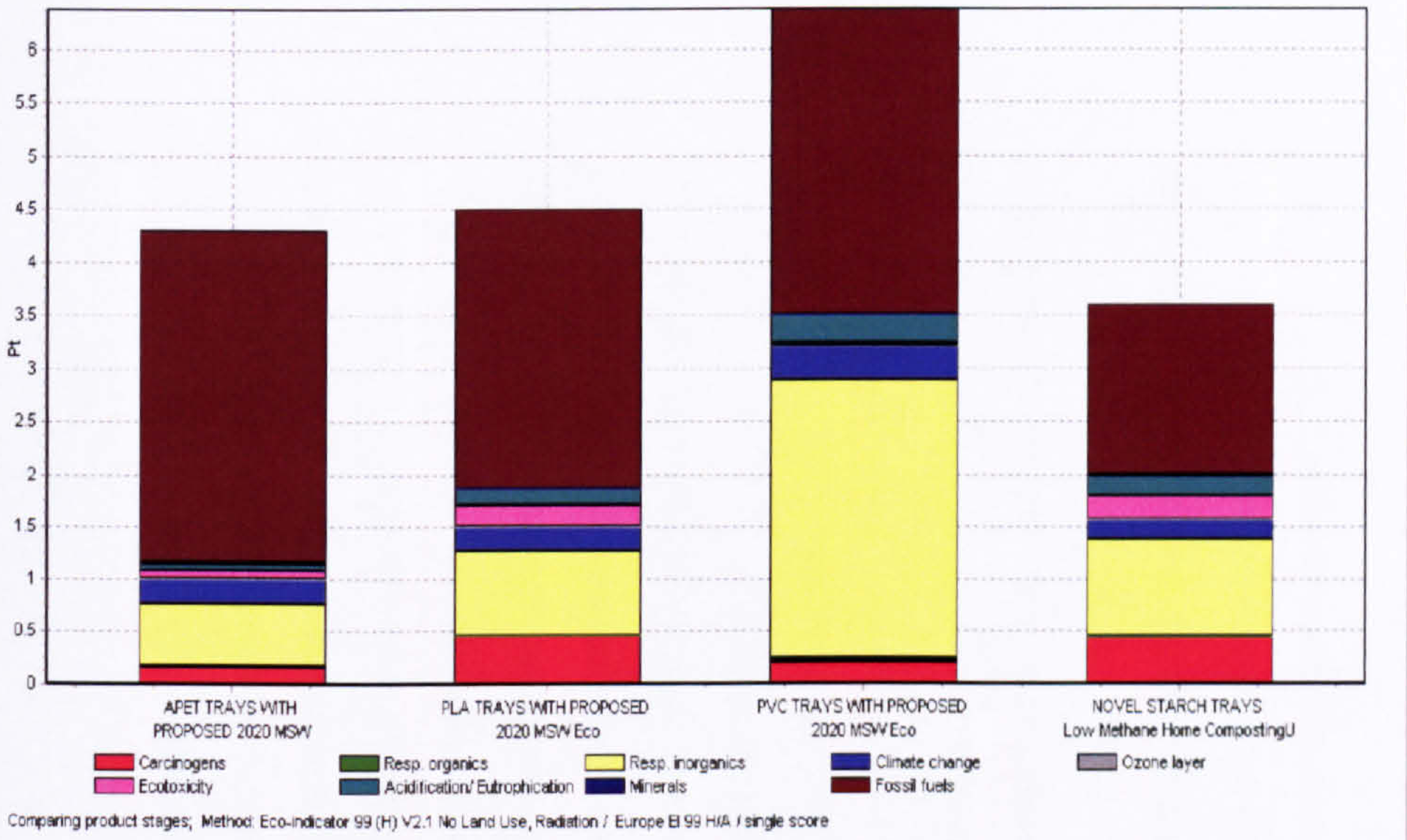


Figure 7.9: Optimum waste disposal option for materials – single score values from weighting (EI99 method).

The environmental impacts of the materials were compared for their favoured waste management option according to Sima Pro. PVC was found to have the highest impact (worst for the environment), particularly in the respiratory inorganic category. Surprisingly PLA came out worse than APET. Novel starch is by far the preferred environmental option, suggesting the need for a material which will break down in a low temperature composting system.

7.10 Sensitivity analysis – Impact assessment method

In order to evaluate the influence of the Impact Assessment method on the outcome of the LCA in terms of polymer performance, the data were also examined using the CML 2000 Impact Assessment method. This is a mid-point system without weighting. The UK Current MSW waste disposal scenario was used in this base case comparison.

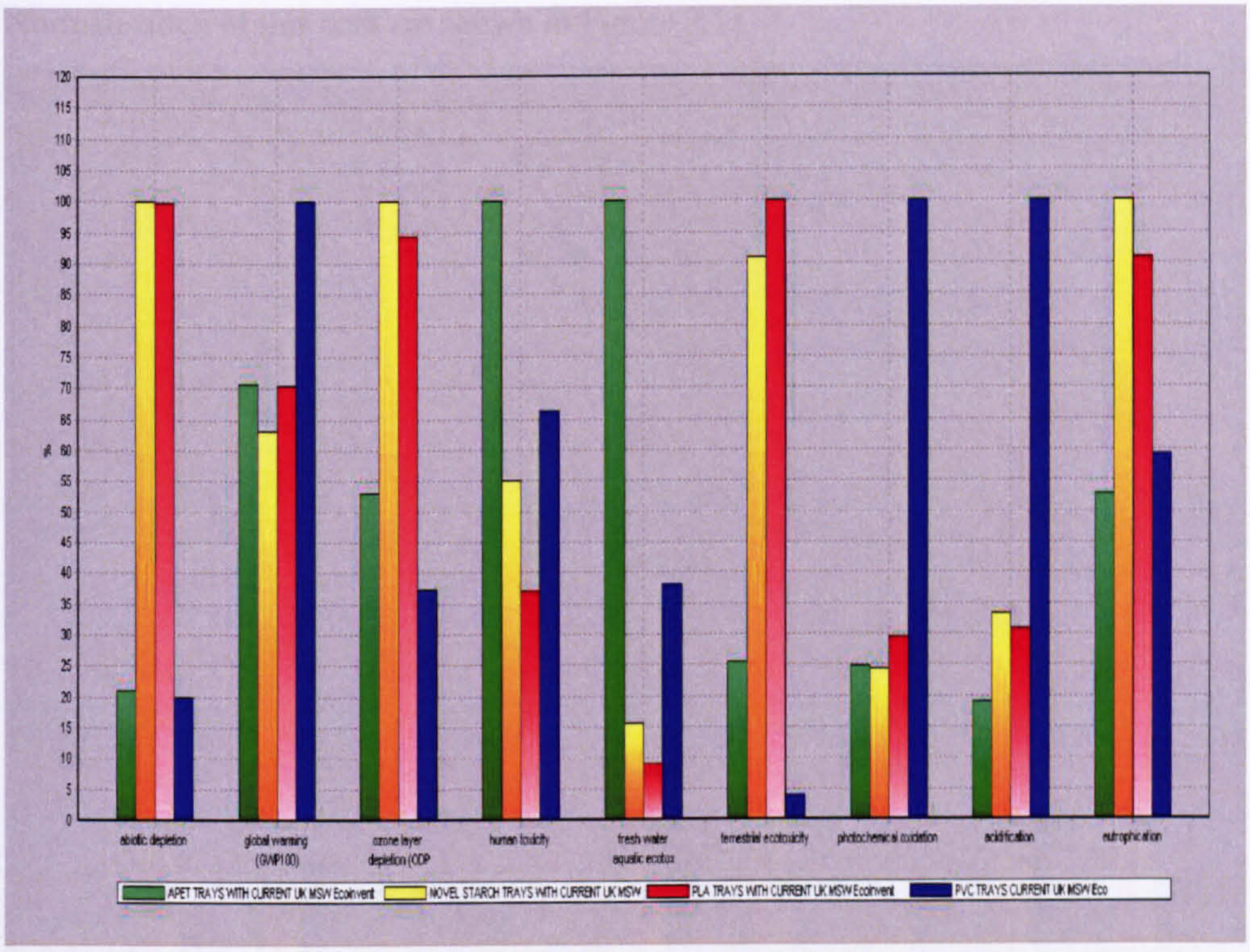


Figure 7.10: Characterised scores for all polymers disposed by Current UK MSW (CML 2000)

The results for the characterised scores in Figure 7.10 show a variable profile for the biodegradable polymers when compared with the fossil based polymers. PLA and Novel starch show lower impacts in the human toxicity, fresh water aquatic eco-toxicity and global warming categories but higher impacts in terrestrial ecotoxicity, eutrophication, ozone layer depletion and abiotic depletion. These are mainly due to the agricultural practices needed for starch production for the biodegradable polymers.

Novel starch and PLA score highly in the case of abiotic depletion in terms of environmental damage. This is mainly due to the energy consumption in manufacturing processes.

It is noted that novel starch has the lowest global warming impact, followed by APET and PLA and PVC has by far the highest.

Normalisation of this data are shown in Figure 7.11

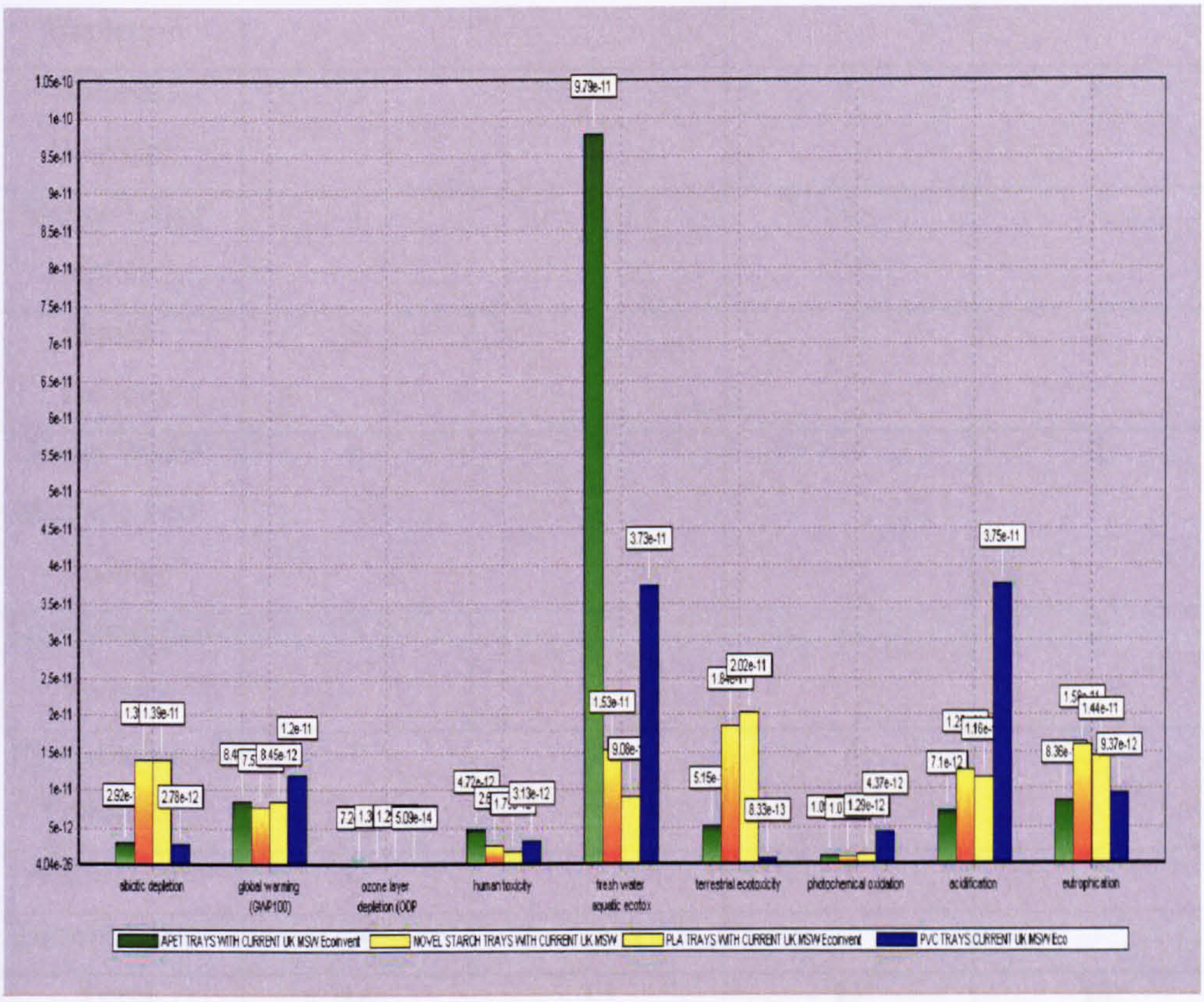


Figure 7.11: Normalised scores for all polymers disposed by Current UK MSW (CML 2000)

Figure 7.11 shows that the Fresh water aquatic ecotoxicity and acidification impact categories have the most significant profile. In these the biodegradable polymers have generally lower impact than the fossil polymers, particularly PVC.

Overall, the results of the CML impact assessment can be summarised in Table 7.2, which presents a simple, un-weighted numerical analysis of the ranking of each polymer by impact category

Table 7.2: Summary of the CML Impact Assessment results

Impact Category	**APET**	**Novel starch**	**PLA**	**PVC**
Abiotic Depletion	1	2	3	0
Global Warming	2	0	1	3
Ozone Layer Depletion	1	3	2	0
Human Toxicity	3	1	0	2
Fresh Water Aquatic Eco-toxicity	3	1	0	2
Terrestrial Eco-toxicity	3	1	0	2
Photochemical Oxidation	1	0	2	3
Acidification	0	2	1	3
Eutrophication	0	3	2	1
Total	**14**	**13**	**11**	**16**

Key to Scores:

- 3 highest impact of the 4 polymers
- 2 second highest
- 1 third highest
- 0 least impact.

i.e: highest score equates to highest impact

The un-weighted CML scores suggest that the polymers rank as follows from least to highest environmental impact (CML 2000):

1. **PLA**
2. **Novel starch**
3. **APET**
4. **PVC**

This compares with the ranking through Eco Indicators 99 (EI 99):

1. **Novel Starch**
2. **APET**
3. **PLA**
4. **PVC**

In summary both impact assessment systems rank PVC as the worst polymer in terms of environmental damage and favour either the novel starch or PLA. On balance Novel starch is the most favoured material in terms of least damage to the environment.

7.11 Results and Conclusions

The LCA supports the studies carried out by environmental pressure groups such as 'Green Peace' and agrees with their Pyramid of Poisonous Plastics, which ranks PVC as the most damaging in environmental terms.

The government and pressure groups have been strongly supporting the need for biopolymers and this LCA further confirms the need for biopolymers such as Novel Starch, which degrades in a low composting systems.

The LCA concludes that biopolymers such as PLA are an improvement in terms of limiting environmental damage. The main difference between Novel starch and PLA is the energy consumed during their production / PLA requires more processing stages to manufacture. The PLA data set used shows that higher levels of transportation are required for PLA than for Novel starch because the PLA used is manufactured in the US.

The research highlighted in chapter 5 suggests that Cargill Dow's anticipated future manufacturing processes will incur a considerable reduction in the fossil fuel required to manufacture PLA. Given this, we can expect to see the profile of PLA reduce in terms of environmental damage, although it currently scores highly in terms of fossil fuel usage.

To date, Novel starch has only been manufactured on a laboratory scale and as such some process improvements and economies of scale can be expected if it were manufactured on an industrial scale. However, not all properties of Novel starch have been evaluated for commercial use (it is a development product). More additives would be needed to assure its commercial success.

The use of two separate impact assessment methods have enabled a more balanced conclusion regarding the LCA of biopolymers compared to oil-based polymers.

In conclusion biodegradable polymers are an environmental improvement over current oil-based polymers.

References

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[1] BSI (1997) Environmental Management – Life Cycle Assessment, Principals and Framework:1997, European Committee for Standardisation, Brussels

[2] Davies G, Murphy R and Song J. (XXXX) ***Assessment of Biodegradable Packaging Materials under Simulated Home Composting Conditions***, submitted to Polymer Degradation and Stability on October 2006.

[3] Waste not, Want not (2002) Strategy Unit strategy@cabinet-office.x.gsi.gov.uk

CHAPTER 8: HOME COMPOSTING OF BIODEGRADABLE POLYMER PACKAGING MATERIALS

8.0 Home Composting of Biodegradable Polymer Packaging Materials

This chapter details several experiments carried out to determine the degree of biodegradation that occurs when bio-based or biodegradable materials are disposed of by a simulated domestic composting regime. The biodegradation was assessed by material weight loss over a twenty-four week period. Additional research was conducted to determine whether it was possible to link the simulated domestic composting regime to a laboratory scale version. This would offer advantages such as shorter time scales, a reduction in specimen materials requirements and the ability to control the experimental conditions. A bioassay report following the PAS 100 standard is also included in this chapter.

8.1 Aim

This research was conducted to determine the extent of biodegradation that can be expected when biodegradable or potentially biodegradable packaging materials are disposed of in simulated home composting. The main aim of the study was to establish whether potentially biodegradable packaging materials would show appropriate levels of biodegradation when home-composted together with green garden waste. Biodegradation was assessed according to material weight loss over a 24 week winter/spring period between November and May in the South East of the UK. The studies were conducted on whole units of food packaging and small specimens of a wider range of materials, with the main emphasis placed on identifying the decomposition performance of a potato starch-based packaging tray (starch), a wood pulp cellulose-based disposable plate (paper) and a maize starch-based polylactic acid (PLA) packaging tray. Additional research was conducted to determine whether it is possible to link the simulated domestic composting regime to a laboratory scale version. If the results correlate and the two can be linked, then materials can be tested on a laboratory scale, which would offer potential advantages such as shorter time scales, lower requirement for specimen material and the ability to control the experimental conditions. The laboratory results could then be used to predict home composting results. The research also aimed to assess the need for specific advice (labelling etc) on biodegradable packaging materials to be used for home composting.

8.2 Materials

The packaging materials used in the different experiments are shown in Table 8.1

Table 8.1. Packaging materials used for simulated home composting

Experimental Name	**Material**	**Commercial (C) / Experimental (E) material**	**Principal Components**	**Small Specimens**	**Whole unit**	**Lab sample 1**	**Lab sample 2**
Potato Starch	Potato starch-based tray	C	Potato starch (< 75%)	✓	✓	✓	✓
Paper	Pressed wood pulp plate	C	Wood pulp 70%: starch size 20 %; other 10 %	✓	✓	✓	✓
PLA	Nature Works™ Polylactic Acid (PLA) tray	E	100 % PLA (grade 2002 D, Cargill-Dow)	✓	✓	✓	✓
Silvergrass	Pressed silvergrass pulp plate	C	*Miscanthus sp* pulp	✓		✓	✓
Coconut	Moulded coconut fibre tray	C	*Cocos nucifera* fibre	✓		✓	
Recycled paper	Moulded recycled paper pulp tray	C	Recycled paper	✓		✓	
Starch Laminate	Apack tray	C	Starch; Mater-Bi®, Novamont Spa. surface overlay	✓		✓	
Starch / PCL	Mater-Bi® -extrudate sample	E	100 % Mater-Bi®, Novamont Spa. (grade SGC 2763)	✓		✓	✓
PP(A)	Polypropylene (PP) with biodegradability additive A	E	90 % PP; 10% bio additive A	✓		✓	
PP(B)	PP with biodegradability additive B	E	90 % PP; 10% bio additive B	✓		✓	
PP(B)+	PP with biodegradability additive B plus chalk filler	E	60 % PP; 10 % bio additive B; 30 % Omyalene chalk	✓		✓	✓
PP/Starch	PP compounded with starch granules	E	88% PP; 10 % starch granules; 2 % other	✓		✓	✓
Plantic	Plantic R1	C	Corn Starch			✓	
Novel Starch 1	Brunel Starch A1	E	Wheat Starch			✓	✓
Novel Starch 2	Brunel Starch A4	E	Wheat Starch			✓	
Novel Starch 3	Brunel Starch A5	E	Wheat Starch			✓	
Novel Starch 4	Brunel Starch A9	E	Wheat Starch			✓	

All % compositions are on a weight basis

8.3 Specimens

Three studies were carried out consisting of exposing materials (see table 8.1) for biodegradation in the composting system. The first study used *whole units* of food packaging manufactured from the three 'main' material types: a potato starch (starch), a pressed wood pulp paper (paper) and polylactic acid (PLA). The second study used *small specimens* these of three materials plus nine other bio-based materials (as described in table 8.1). A third study which used even smaller specimens of these twelve bio-based materials plus a further five (table 8.1), all of which are either currently used or have the potential to be used in the food packaging industry.

Study 1: Full size 'whole units' replicate samples of potato starch packaging trays, moulded wood pulp plates and polylactic acid (PLA) sandwich trays were co-composted with green garden waste.

Study 2: Small (~ 25mm^2) replicate specimens of twelve materials were pre-weighed, sealed in nylon mesh packets, placed in stainless steel racks and exposed for biodegradation with green garden waste. Six of the twelve were derived from materials used experimentally and six were derived from industrial materials designed to be biodegradable.

Study 3: Smaller (~ 20mm^2) replicate specimens of seventeen materials were pre-weighed, sealed in nylon mesh packets, placed in food containers and co-composted with herbaceous material, which had already been composting for 6 months in a domestic composter.

8.4 Equipment

- 160 litre Milko Compost bins from Staright
- Top pan balance weighing to three decimal places
- Timberwolf TW 150DHB Shredder
- Face guard and ear protectors
- Boiler Suit and safety shoes
- 2 horse power petrol strimmer
- Small tractor and trailer
- Pitch fork
- 16 litre bucket
- 13 litre Sankey high capacity watering can, with fine rose
- Scissors
- Stapler and staples
- Net curtain material
- Stainless steel mesh
- Snips
- Various sized plastic sample bags
- Garden mat and bag from B & Q
- Garden gloves
- Digital Camera
- Glass Petri Dishes
- Small Scrapers
- Small brushes

8.5 Experimental Details

This section describes the experimental methods of the full size 'whole units' experiment, the small specimen experiment including the PAS 100 seed germination test and the two laboratory experiments.

8.5.1 Full Size 'Whole Units' and Small Specimen Compost Experiment Procedure

An initial phase of define the research objective, carry out a literature search into biodegradable polymers and composting, and source commercially available polymers that claim to be biodegradable was completed.

The next stage of the research project was to purchase/hire suitable equipment (see section 8.3 for a list of equipment used) and source suitable herbaceous materials. The herbaceous materials, which were from a known source to eliminate any unwanted pesticides and chemicals, were chopped using a Timberwolf TW 150 DHB shredder to obtain uniformity. Figures 8.1 and 8.2 show photographic images of the shredder in use.

Figure 8.1: Herbaceous materials ready to be shredded

Figure 8.2: Herbaceous materials shredded into a more uniform format

The chopped herbaceous material was manually mixed with freshly cut grass (in the proportions ~80% herbaceous materials to ~20% grass), which made up the 'base mixture'.

A sixteen-litre bucket was filled with the herbaceous and grass 'base mixture' and weighed using a top pan balance. This weighing process was repeated several times and an average weight of mixture per litre calculated. The 160-litre Milko compost bins were then filled with the herbaceous/grass 'base mixture' (see figure 8.3) with an approximate weight of 26.6 kg. The herbaceous/ grass mixture was allowed to compost for a period of 4 weeks in order to establish microflora/fauna.

Figure 8.3: One of the 160 litre Milko compost bins filled with a herbaceous/ grass mixture

The composter bins were set up in October 2004 and allowed to establish for four weeks before the packaging materials were introduced in November. The moisture content and temperature of the compost were recorded at set intervals during the research project. Rainfall and atmospheric temperatures were recorded throughout the project lifetime using monitoring equipment from Imperial College Silwood Park.

During the initial four-week composting period the commercially available polymers that claim to be biodegradable were prepared for the composting project. This preparation involved the materials being cut into specimens of ~ 25mm^2 and then labelled and conditioned (see figure 8.4). Conditioning involved all the materials being stored under the same conditions, room temperature and humidity for 5 days.

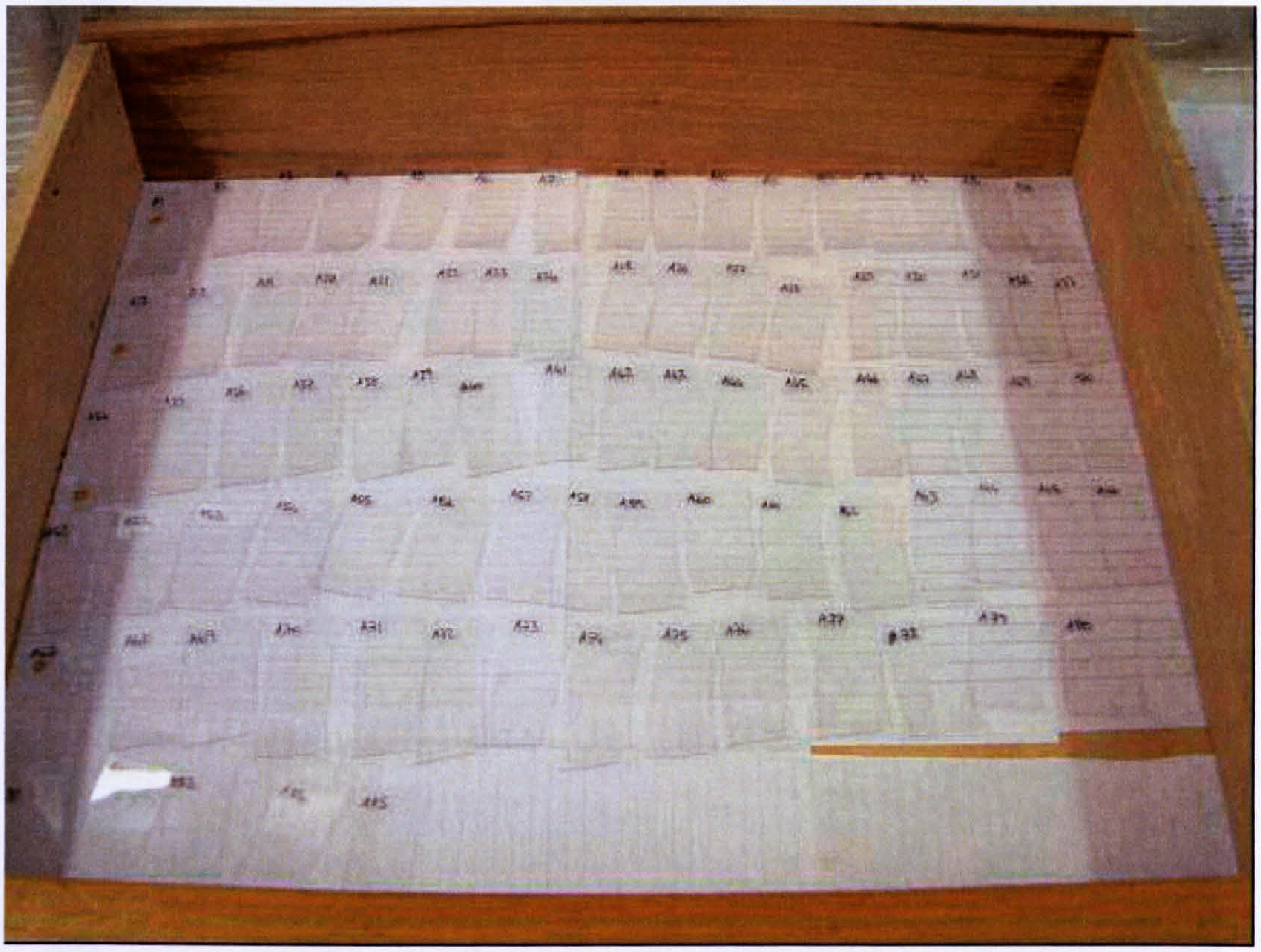


Figure 8.4: Polylactic acid material which has been cut, labelled and is being conditioned

After the conditioning period the specimens were weighed to determine their initial weight and placed into nylon sample bags. These consisted of nylon netting stapled together and labelled so that it would be possible to retrieve and weigh the samples from the composting bin. The bagged specimens were placed into stainless steel meshes (figure 8.5) for easy location and removal from the composting bins.

Figure 8.5: Bagged specimens randomly placed into the stainless steel mesh prior to closing

Maps of the bagged specimens were drawn for easy location of the samples should they become spoiled and the labels unreadable during the composting phase. (See figure 8.6) for an example of a map.

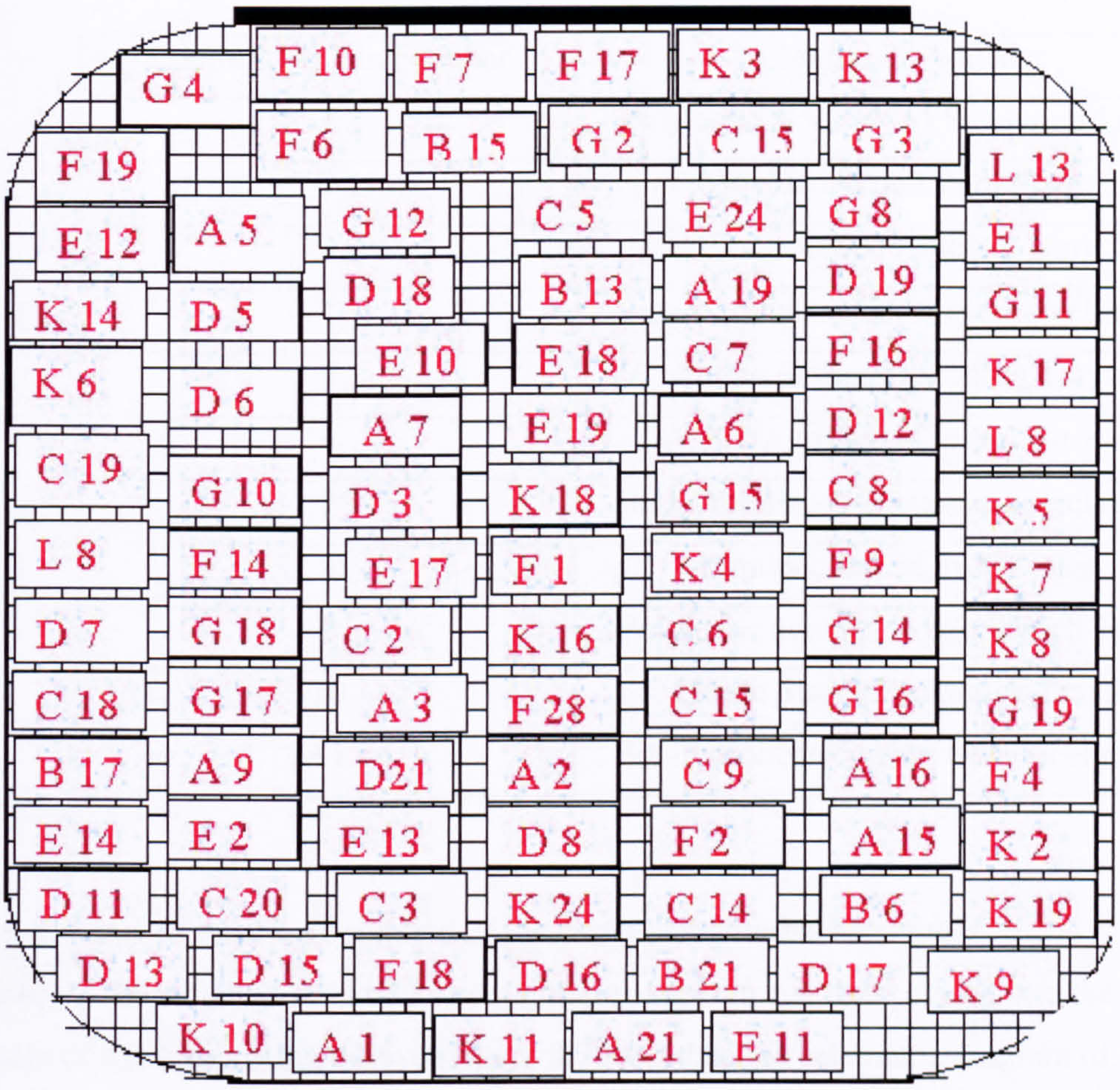


Figure 8.6: Example of a map drawn to aid location of the specimens

After the four-week composting period was complete the composting bins were labelled (table 8.2).

Table 8.2: Composting bin numbers including materials added

Composting Bin Number	Materials Added
1	Polylactic acid (PLA) Sandwich Trays
2	Moulded Wood Pulp Plates
3	None Added (Control Bin)
4	Small replicates in stainless steel mesh
5	Potato Starch Packaging Trays
6	None Added (Control Bin)
7	Small replicates in stainless steel mesh
8	Moulded Wood Pulp Plates
9	Polylactic acid (PLA) Sandwich Trays
10	Potato Starch Packaging Trays
11	Small replicates in stainless steel mesh

Bins 4, 7 and 11 were half emptied of the composting herbaceous/grass 'base mixture'. The stainless steel racks containing the specimens were placed into the middle of the composting bin (see figure 8.7 for a detailed schematic diagram of the composting process) and the herbaceous material was placed on top of the stainless steel rack in the composting bin.

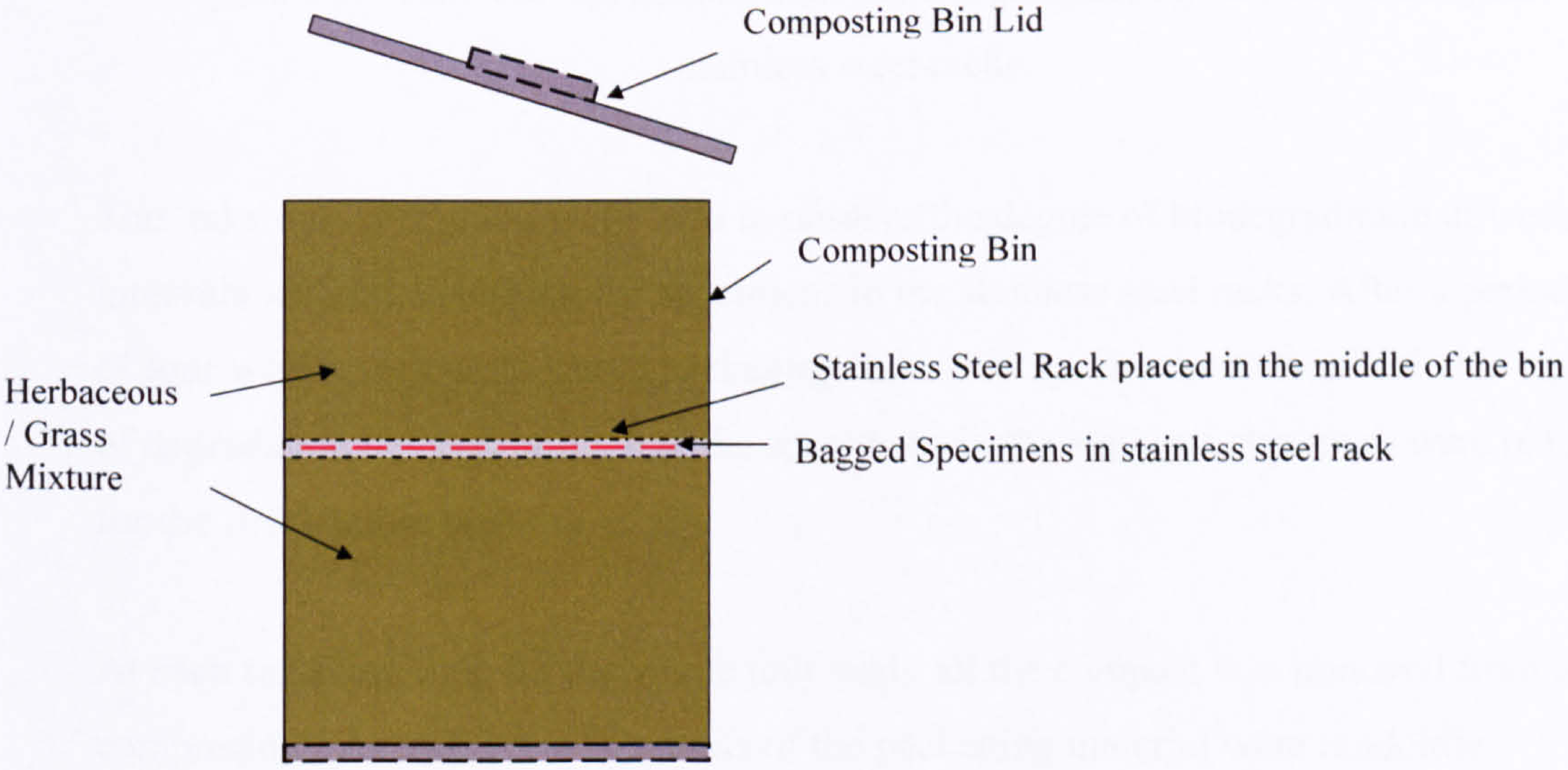


Figure 8.7: A detailed schematic diagram of the composting equipment

In additional to the specimens in the stainless steel rack, several 'take out' specimens of potato starch packaging were added to the herbaceous/grass mixture in the composting bins (figure 8.8).

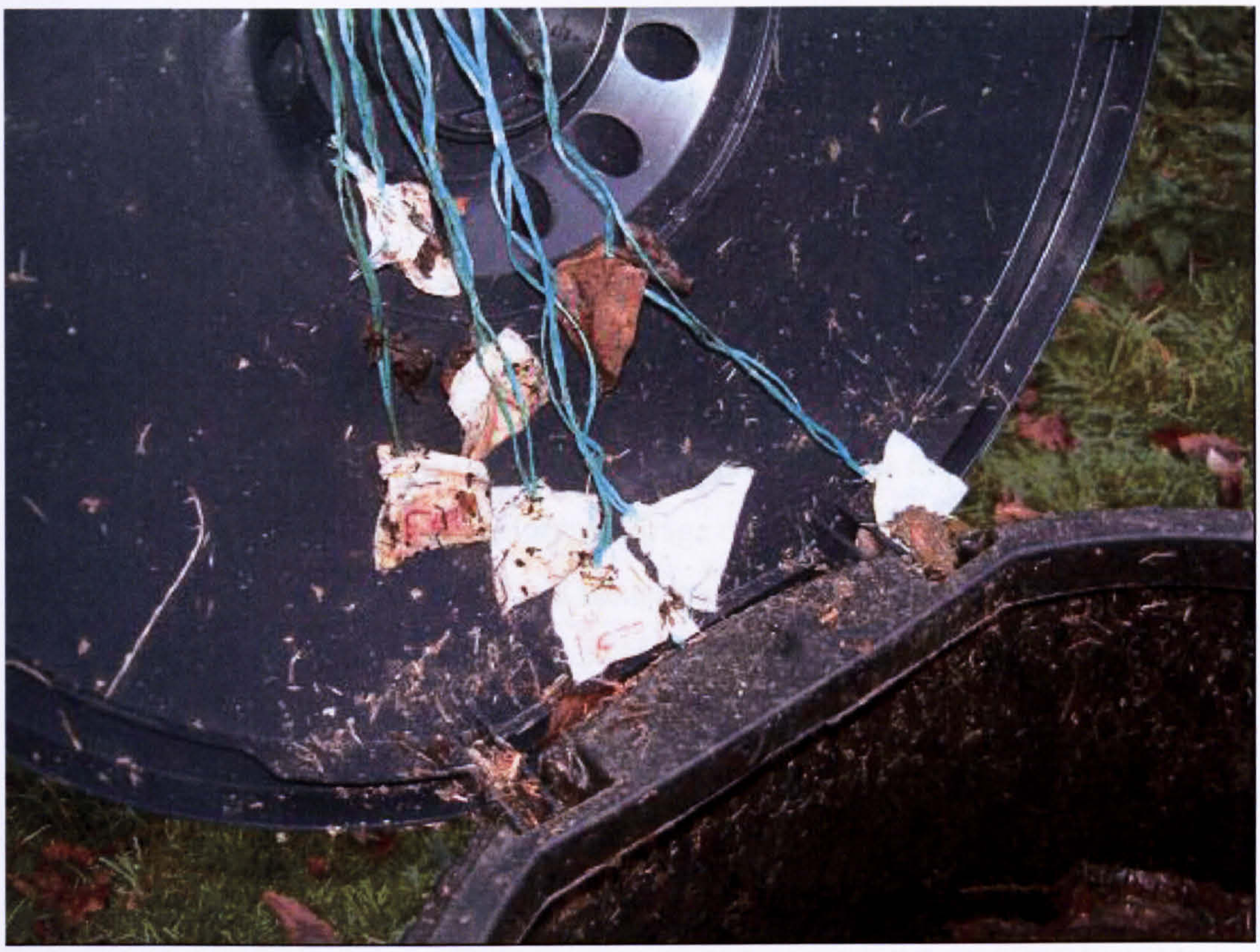


Figure 8.8: 'Take out' specimens added to the composting bins containing the stainless steel racks.

The 'take out' specimens were used to observe the degree of biodegradation at weekly intervals without disturbing the specimens in the stainless steel racks. After a period of four weeks, the potato starch packaging 'take out' specimens showed suitable signs of degradation demonstrating that the specimens in the stainless steel rack were ready for the first sample time.

At each sampling time for the whole unit study all the compost was removed from the composting bins and five whole units of the packaging material were randomly retrieved from the compost as intact as possible. A visual assessment was conducted on the whole units of the 3 main materials to obtain a general assessment of the extent to which the materials showed signs of moisture pick up, microbial attack, grazing or other breakdown and fragmentation and loss of integrity in order to evaluate integration into the compost matrix. A combined ranking scale with five levels from “no degradation”(level one) to “complete integration into compost”(level five) was used to express results (Table 8.3). The trays were placed into sealed food storage containers for transportation to Imperial College’s South Kensington Biology laboratory and all the remaining contents were returned to the composting bins to await further sampling times.

A similar procedure was carried out for the small specimens. At each sampling time the compost material on top of the racks was manually taken out of the composting bins. The stainless steel racks were extracted from the composting bins and selected specimens for that sample time were removed, placed into plastic petri dishes, labelled and then placed into sealed food storage containers for transportation to the laboratory. The stainless steel rack and the herbaceous/grass ‘base mixture’ were placed back into the composting bin to await further sampling times. This process was repeated for the other two bins containing stainless steel racks.

Upon arrival at the South Kensington laboratory the whole units were individually weighed whilst wet then placed in a pre-weighed glass petri dish and weighed using a 3 decimal place top pan balance. To obtain the dry masses of the samples, the glass petri dishes were heated to 105°C for 24 hours and then cooled in the presence of silica gel. The moisture content and mass loss per whole unit was then calculated and compared to an average value for that type of whole unit (established from previous weighings of 50 representative whole units, corrected for initial material moisture content). The dried samples were labelled and placed in sealed containers for future reference.

The small specimens were individually cut out of the sample bags using scissors and a visual inspection carried out. Figure 8.9 shows a detailed close up of a degraded potato starch sample. A scraper and forceps were used to remove the specimen from the mesh.

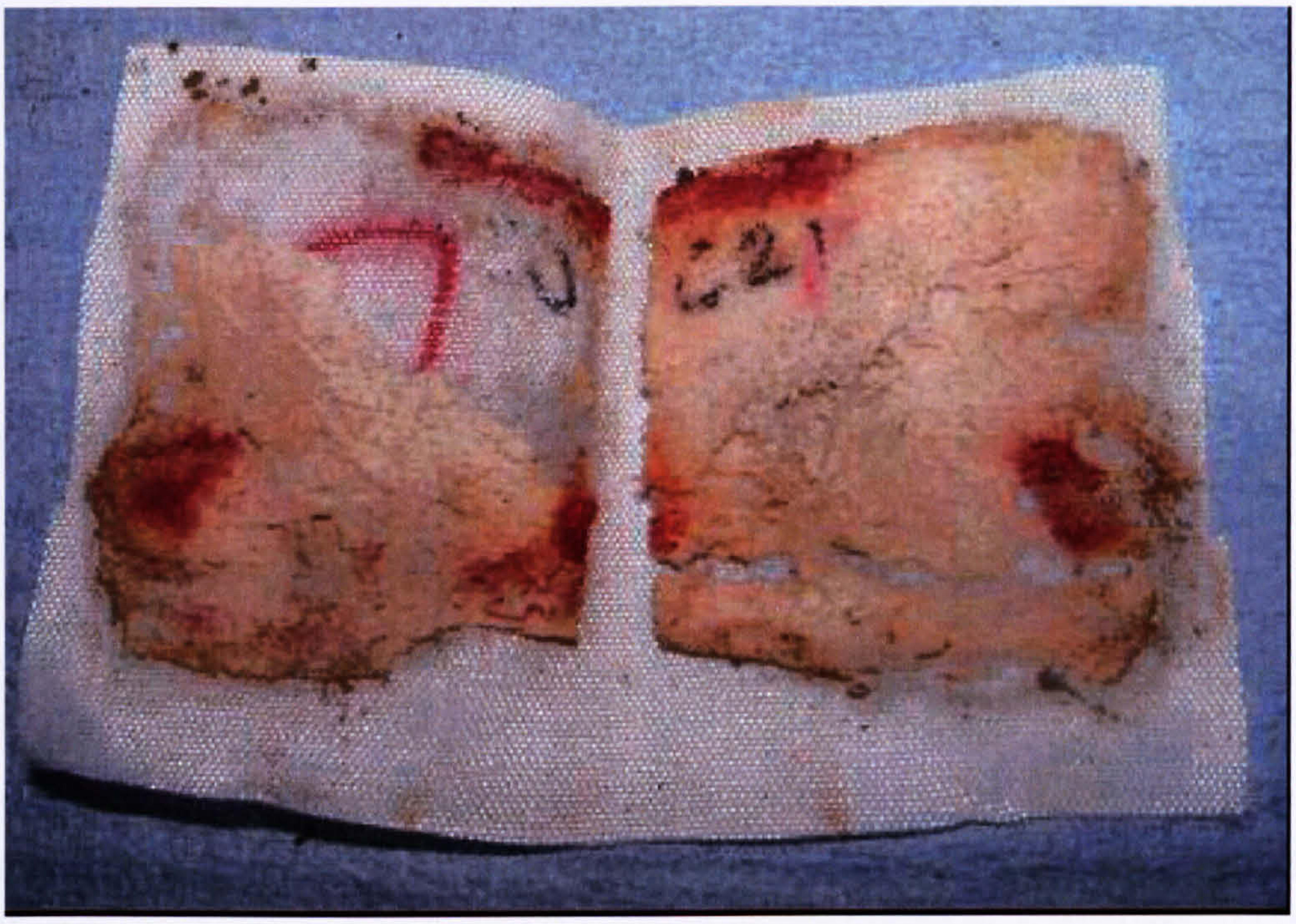


Figure 8.9: showing a detailed close up of a degraded potato starch sample

The degraded specimen was then placed in a pre-weighed glass petri dish and weighed 'wet' using a 3 decimal place top pan balance. The moisture content (dry wt basis) and mass loss were calculated by comparison to the initial values for each specimen prior to test (after correction for initial moisture content). Data for material weight loss was averaged and standard deviations calculated. The dried samples were labelled and placed in sealed containers for future reference.

8.5.2 Bioassay (PAS 100) Seed Germination and Seedling Development in Resulting Composts Procedure

A bioassay of the composts from the whole unit test and the control compost was conducted in accordance with the Publicly Available Standard (PAS) 100 (2002) 'Specification for composted materials'[1].

PAS 100 is intended for composts which result from source-segregated biodegradable materials and specifies the minimum quality of compost needed to reduce any risk to humans, animals, plants and the environment to acceptable levels. The objective is to produce reliably safe, effective composts suitable for agricultural horticultural land restoration, soft landscaping, sports recreation and other markets. The compost is graded according to its particle size and additives. There is a driving force to reduce the millions of tonnes of biodegradable waste that currently end up in landfill in the UK. Compliance with the standard is important, as compost can potentially contain hazards materials.

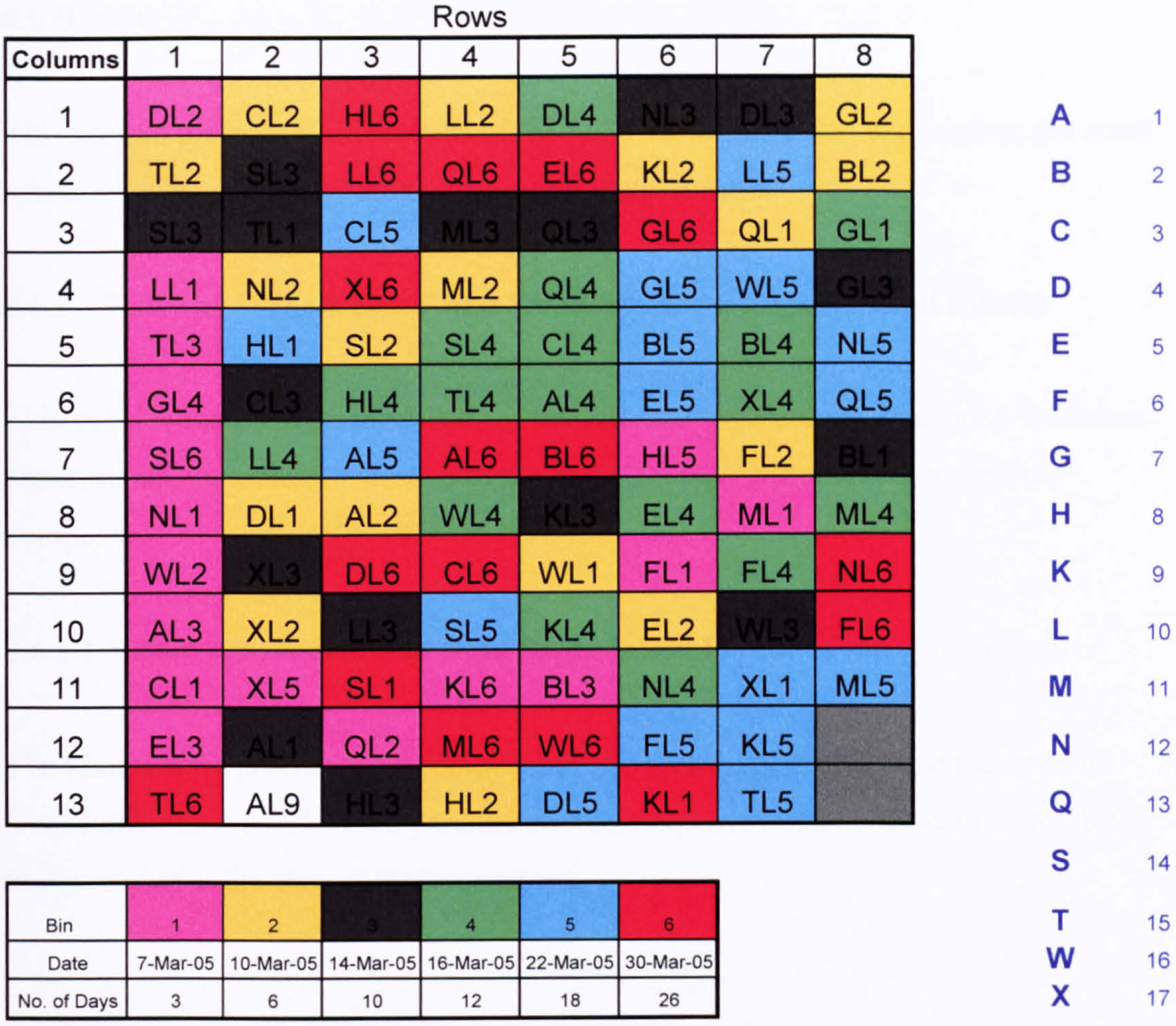
The PAS 100 method to assess plant response and contamination by weed propagules was followed. F1 tomato seeds (variety Shirley, Sutton Seeds, UK) were placed in the prescribed mixture of background growth medium and test compost in seed trays and maintained with regular watering at a temperature of 20 – 25°C in a naturally light greenhouse in early summer 2005 over the 28 day period of the test. Seed germination, fresh plant mass, abnormalities and weed emergence were recorded in accordance with PAS 100. The assessment of weed propagules is relevant to an industrial compost process as part of a commercial product quality assurance but, due to the low temperatures attained in domestic composting, the sterilisation of such propagules is not a target for such systems.

8.5.3 Laboratory Scale Compost Experiments One and Two Procedure

Similar lab scale research projects were also set up in order to simulate the domestic composting experiment in a controlled environment of 25°C, the aim being to link all the projects and predict the outcome of the whole tray composting project without the need for large quantities of materials or lengthy project time scales. Five litre food containers (figure 8.10) were used instead of composting bins.

Figure 8.10: Five Litre food containers used instead of composting bins

A map similar to that used in the domestic composting project was drawn up (see figure 8.11). The container was divided up into a grid format with each square housing a sample. The samples were coded according to material type and extraction date; randomly distributed across the grid and then systematically extracted on the relevant sampling days. Figure 8.11 shows the grid layout with each specimen's location and its date of extraction. The only differences in the procedures between the domestic experiment and the laboratory scale experiment were shorter time scales and smaller and container sizes. Two laboratory scale experiments were performed for different time periods. The first experiment was performed for 27 days and the second for 60 days.



	Rows							
Columns	1	2	3	4	5	6	7	8
1	DL2	CL2	HL6	LL2	DL4	NL3	DL3	GL2
2	TL2	SL3	LL6	QL6	EL6	KL2	LL5	BL2
3	SL3	TL1	CL5	ML3	QL3	GL6	QL1	GL1
4	LL1	NL2	XL6	ML2	QL4	GL5	WL5	GL3
5	TL3	HL1	SL2	SL4	CL4	BL5	BL4	NL5
6	GL4	CL3	HL4	TL4	AL4	EL5	XL4	QL5
7	SL6	LL4	AL5	AL6	BL6	HL5	FL2	BL1
8	NL1	DL1	AL2	WL4	KL3	EL4	ML1	ML4
9	WL2	XL3	DL6	CL6	WL1	FL1	FL4	NL6
10	AL3	XL2	LL3	SL5	KL4	EL2	WL3	FL6
11	CL1	XL5	SL1	KL6	BL3	NL4	XL1	ML5
12	EL3	AL1	QL2	ML6	WL6	FL5	KL5	
13	TL6	AL9	HL3	HL2	DL5	KL1	TL5	

Bin	1	2	3	4	5	6
Date	7-Mar-05	10-Mar-05	14-Mar-05	16-Mar-05	22-Mar-05	30-Mar-05
No. of Days	3	6	10	12	18	26

A	1
B	2
C	3
D	4
E	5
F	6
G	7
H	8
K	9
L	10
M	11
N	12
Q	13
S	14
T	15
W	16
X	17

Figure 8.11: Map for the lab scale composting research

8.6 Results

This section presents all the results of the full size 'whole units' experiment, the small specimen experiment and the two laboratory experiments.

8.6.1 Full Size 'Whole Units' and Small Specimen Experimental Results

This sub-section presents the results of the full size 'whole units' and small specimen experiments, including the results of the PAS 100 seed germination of the final composts.

8.6.1.1 Visual Assessment and Bulk Degradation Profile of the Composters

The temperature profile in the compost bins (Figure 8.12) showed that the systems were functioning as a low temperature composting environment between 15 to 18°C in November at the start of the experiment.

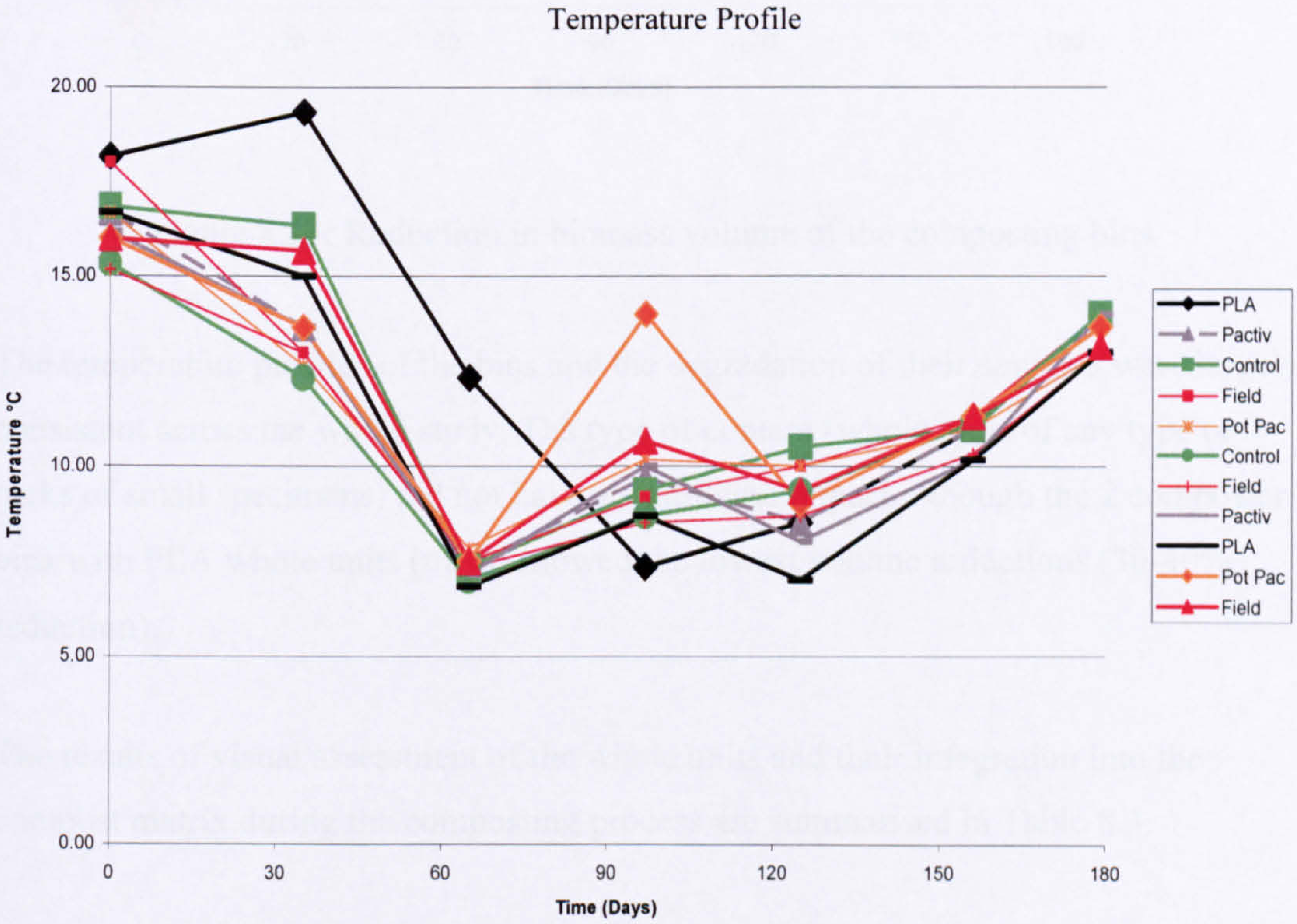


Figure 8.12: Temperature profile in the compost bins (November to May 2005)

This profile dropped to a low of approximately 8-10 °C in Jan/Feb/March and then rose to approximately 14 °C in May. The lowest composter bin temperatures reflect the typical lower winter temperatures in January and February in the South East of the UK. All composter bins showed an acceptable level of reduction in biomass volume during the composting period, equating to about half of the original volume (Figure 8.13).

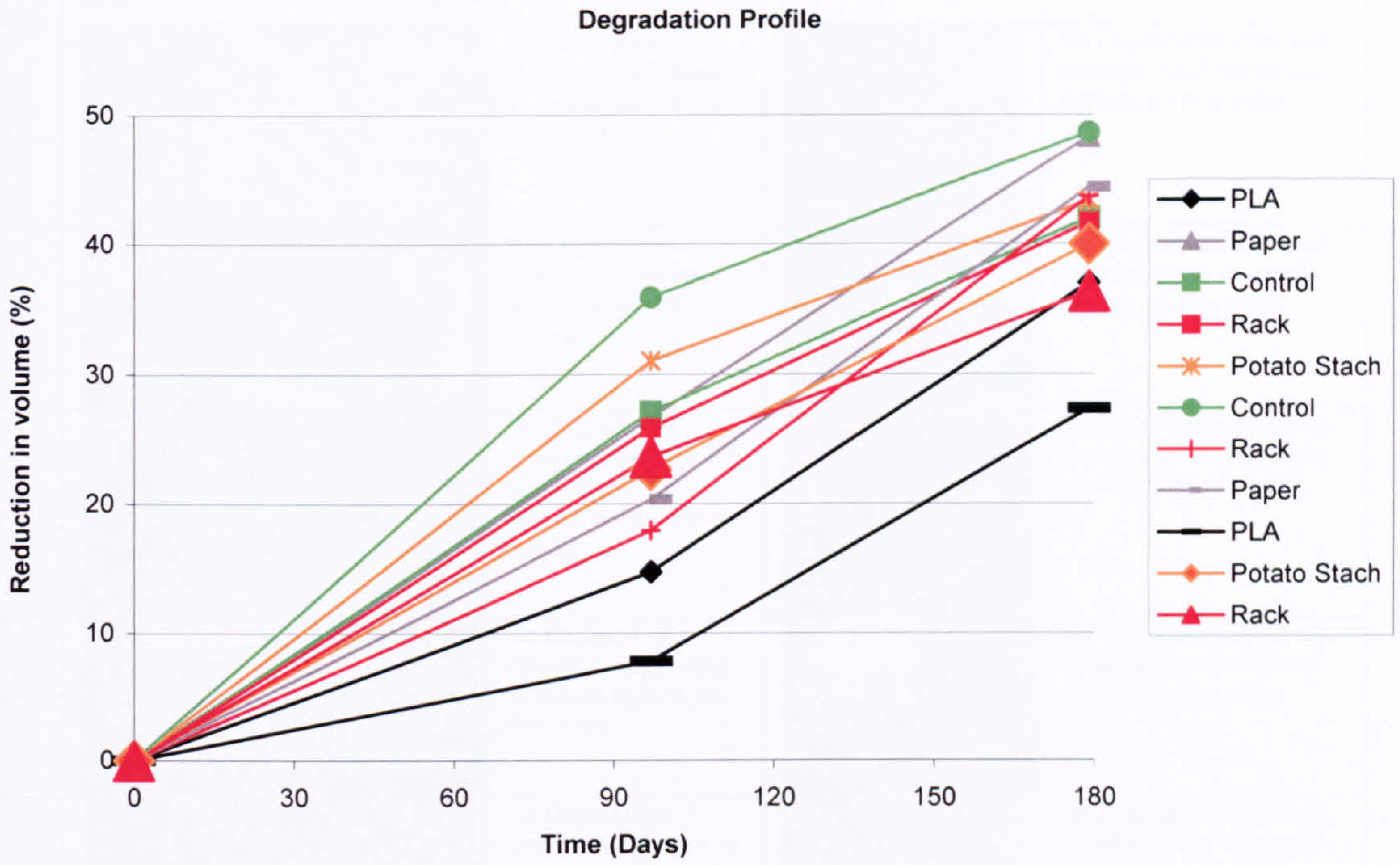


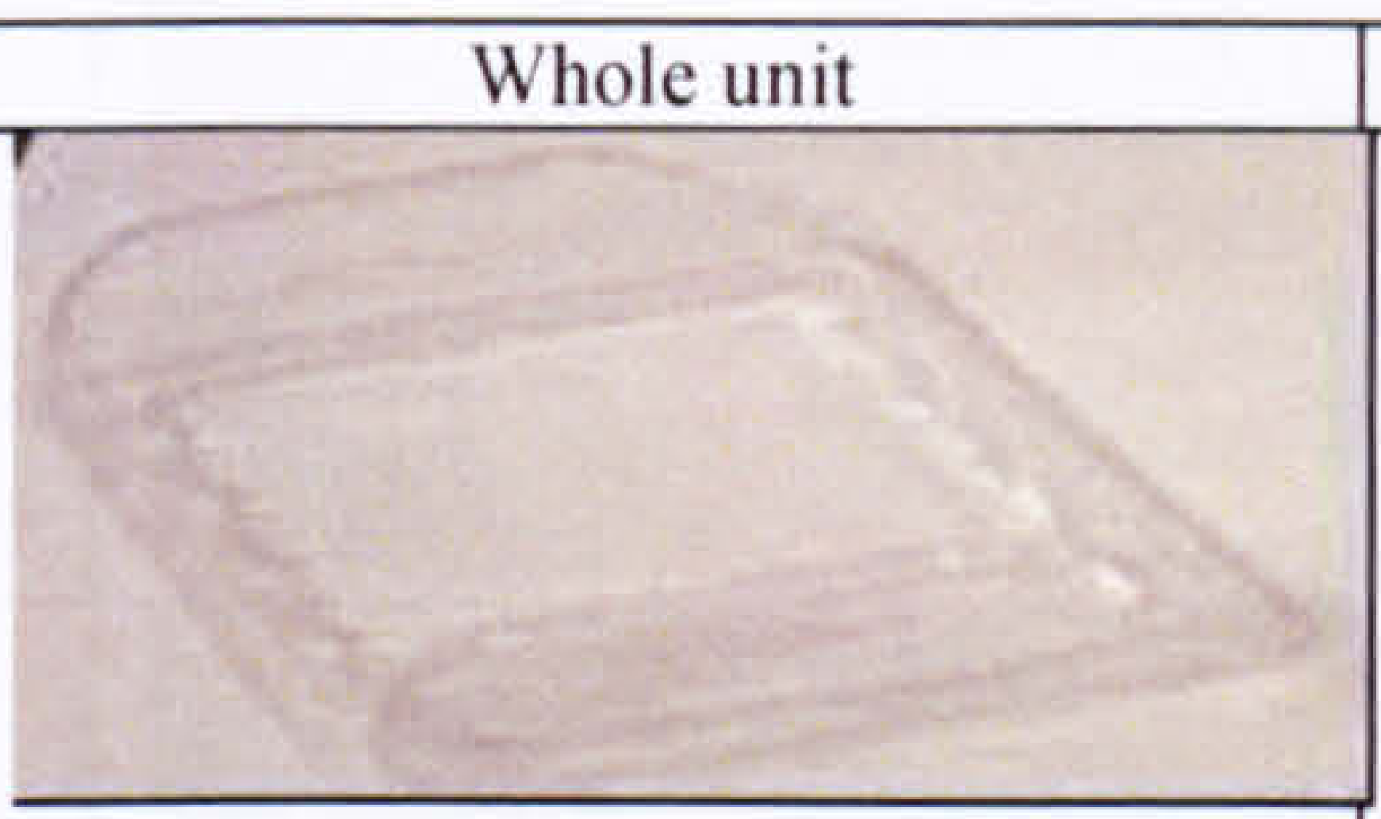
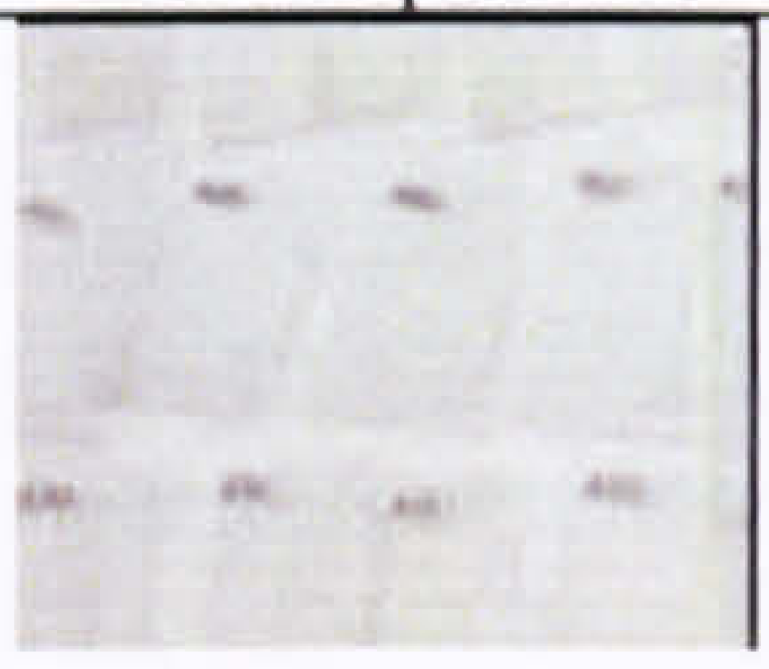
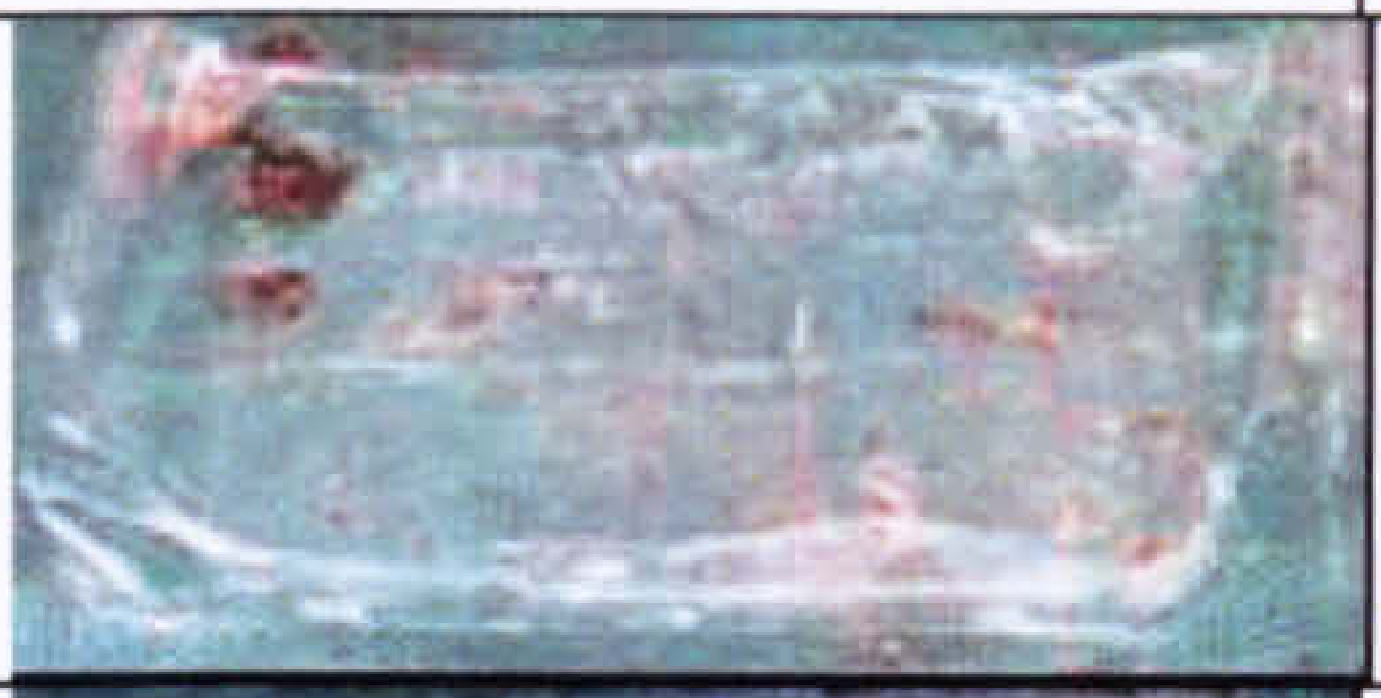
Figure 8.13: Reduction in biomass volume of the composting bins

The temperature profiles of the bins and the degradation of their contents were largely consistent across the whole study. The type of content (whole units of any type or racks of small specimens) did not have a significant impact although the 2 composter bins with PLA whole units (trays) showed the lowest volume reductions (30-40% reduction).

The results of visual assessment of the whole units and their integration into the compost matrix during the composting process are summarised in Table 8.3.

Table 8.3: Visual assessment of packaging materials during simulated home composting

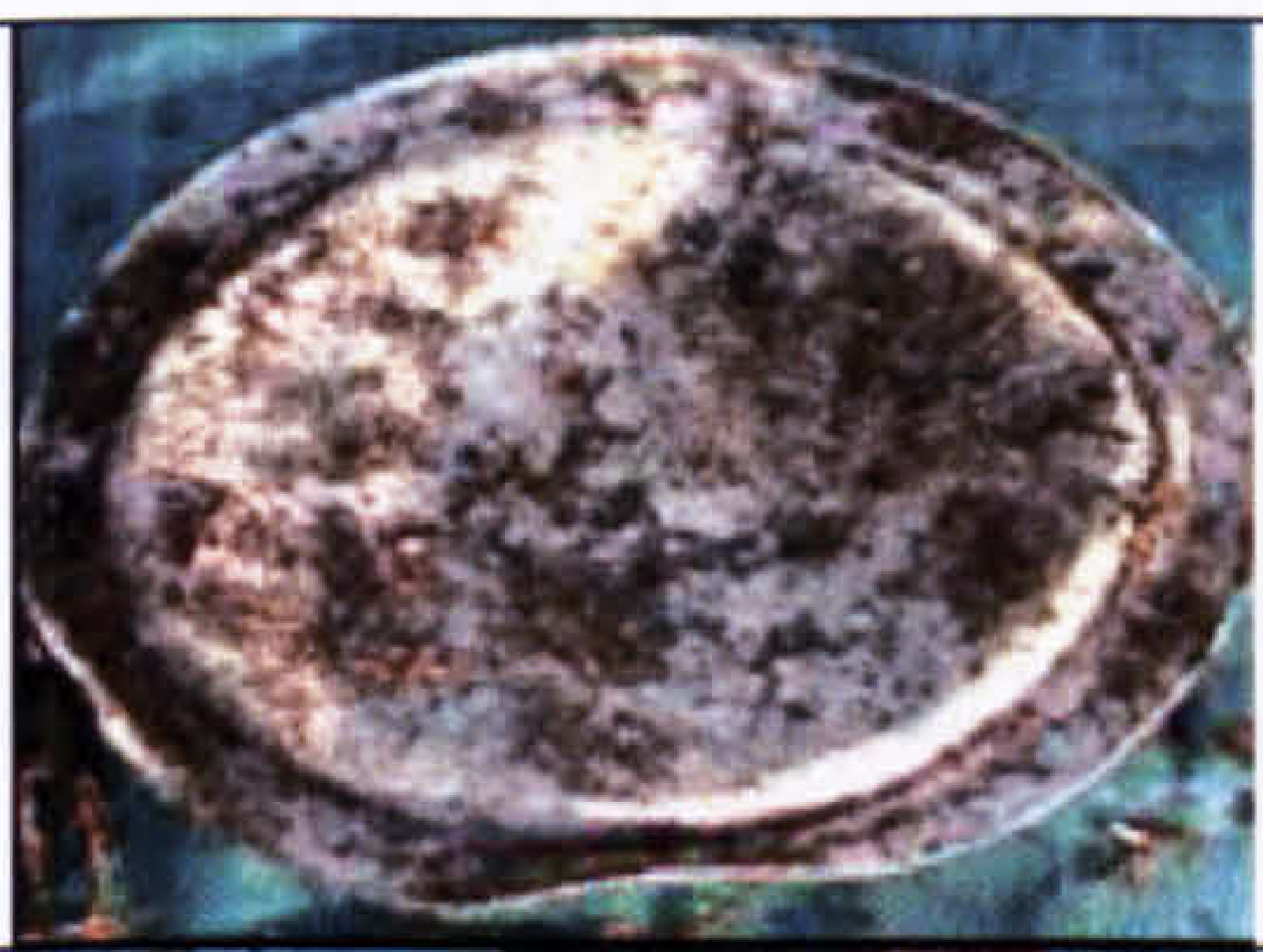
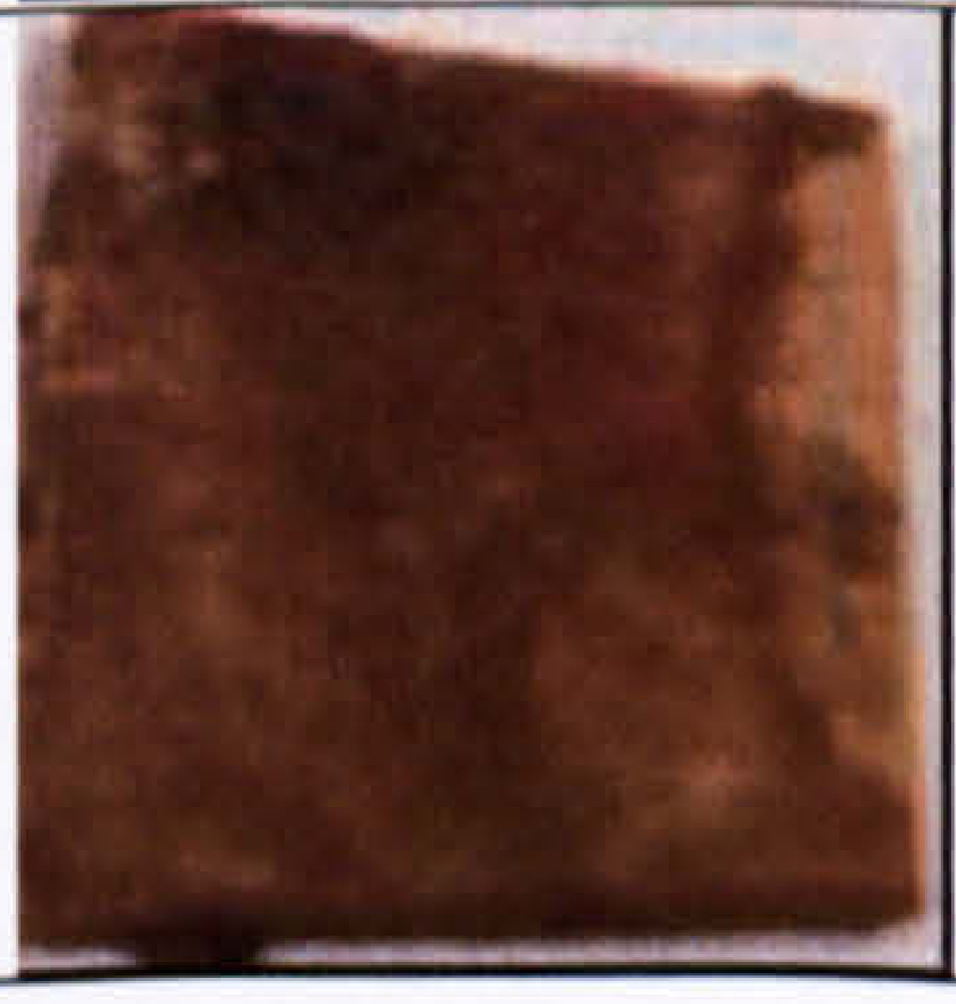
PLA tray

Day	Whole unit	Description	Small specimen	Description
0		Tray in its original state		Sample in its original state
35		No Degradation observed, trays intact, no mould growth, no free water		No Degradation observed, samples intact, no mould growth, no free water
65		No Degradation observed, trays intact, no mould growth, no free water		No Degradation observed, samples intact, no mould growth, no free water
97		No Degradation observed, but tray shows signs of damage due to manual turning.		No Degradation observed. Samples intact, no mould growth, no free water
124		No Degradation observed, trays intact, no mould growth, no free water		No Degradation observed, samples intact, no mould growth, no free water
156		No Degradation Trays showed signs of breaking up this is due to manual turning rather than degradation		No Degradation observed, samples intact, no mould growth, no free water
190		No Degradation Tray showing some mechanical damage with small fragments missing.		No Degradation observed, samples intact, no mould growth, no free water

Potato starch tray

No. of days in Compost	Whole unit	Description	Small specimen	Description
0		Original tray		Original sample
35		Obvious signs of degradation		Obvious signs of degradation
65		Obvious signs of degradation		Sample has partially degraded.
97		Tray has broken up and it is no longer possible to remove from compost.		Sample has degraded and small remains can be obtained.
124		Tray has broken up and it is no longer possible to remove from compost.		Sample has degraded and small remains can be obtained.
156		Tray has dispersed into tiny fragments, unable to retrieve.		Very small amounts of sample left.
190		Tray has dispersed into tiny fragments, unable to retrieve.		Very small amounts of sample left.

Paper plate

No. of days in Compost	Whole unit	Description	Small specimen	Description
0		Tray in original state.		Sample in original state.
35		Tray shows sign of mould growth and particles adhering themselves to the tray.		Sample shows signs of wetting.
65		Tray very dry and therefore water added to the composting system.		Sample very dry and therefore water added to the composting system.
97		Further signs of degradation and the tray is breaking up.		Further signs of degradation
124		Further signs of degradation and the tray is breaking up.		Further signs of degradation
156		Obvious signs of degradation, tray broken up and bits missing, lots of mould growth.		Obvious signs of degradation, lots of mould growth.
190		Unrecognisable as a tray, very fragile to touch.		Very fragile to touch.

Alternative for Table 8.3

Property	**Material**	1	2	3	4	5	6
Moisture	**Starch**	✱✱	✱✱	✱✱✱	✱✱✱✱	✱✱✱✱	✱✱✱✱
	Paper	✱	✱	✱✱	✱✱	✱✱✱	✱✱✱
	PLA	-	-	-	-	-	-
Microbial	**Starch**	✱✱	✱✱✱	✱✱✱	✱✱✱✱	✱✱✱✱	✱✱✱✱
	Paper	✱	✱	✱✱	✱✱	✱✱	✱✱
	PLA	-	-	-	-	-	-
Fragmentation	**Starch**	✱	✱✱	✱✱✱	✱✱✱	✱✱✱	✱✱✱
	Paper	-	✱	✱	✱	✱✱	✱✱
	PLA	-	-	-	-	-	✱
Integration	**Starch**	✱	✱✱	✱✱✱	✱✱✱	✱✱✱	✱✱✱
	Paper	-	-	-	-	✱	✱✱
	PLA	-	-	-	-	-	-

Key:
- = property unsuitable for degradation into compost
✱ = property just appropriate for a low level of degradation into compost
✱✱ = property at a good level for degradation into compost
✱✱✱ = property at a very high level for degradation into compost – supportive of a maximum degradation rate
✱✱✱✱= could not be assessed as conversion into compost was complete

In general, the breakdown of the small specimens was visually very similar to that of the whole units, although it tended to be less extensive than with the whole units. This is likely to be due to protective effects of the mesh packets and racks.

Visual assessments of the whole units clearly demonstrated that complete disintegration and incorporation of the starch trays into the compost matrix had occurred after 90 days of composting. The paper plate material had also extensively broken down over the composting period, although it was possible to distinguish elements of the original plate material after 180 days, despite their being heavily discoloured and lacking structural integrity. The PLA polymer showed no visual evidence of microbial breakdown after 180 days, although fragments had broken off some trays. This was not considered to be disintegration as a result of biodegradation but was attributed to disturbance of the bins and mechanical damage when retrieving samples.

There was a large variation in the degree of biodegradation, which depended on the type of material used, Table 8.1. Overall, three groups were identified:

1) ***Fast degraders***: approx 70% weight loss at 90 days – principally starch materials
2) ***Medium degraders***: approx 40% weight loss at 90 days – principally plant fibres or cellulose
3) ***Slow degraders***: less than 5% weight loss at 90 days – principally PLA, starch/polycaprolactone blend and modified polypropylenes

8.6.1.2 Mass Loss and Moisture Content Results

The results for determination of mass loss (extent of biodegradation) for the 3 main material types (Starch, paper, PLA) are given in Figures 8.14 and 8.15 for whole units and small specimens respectively.

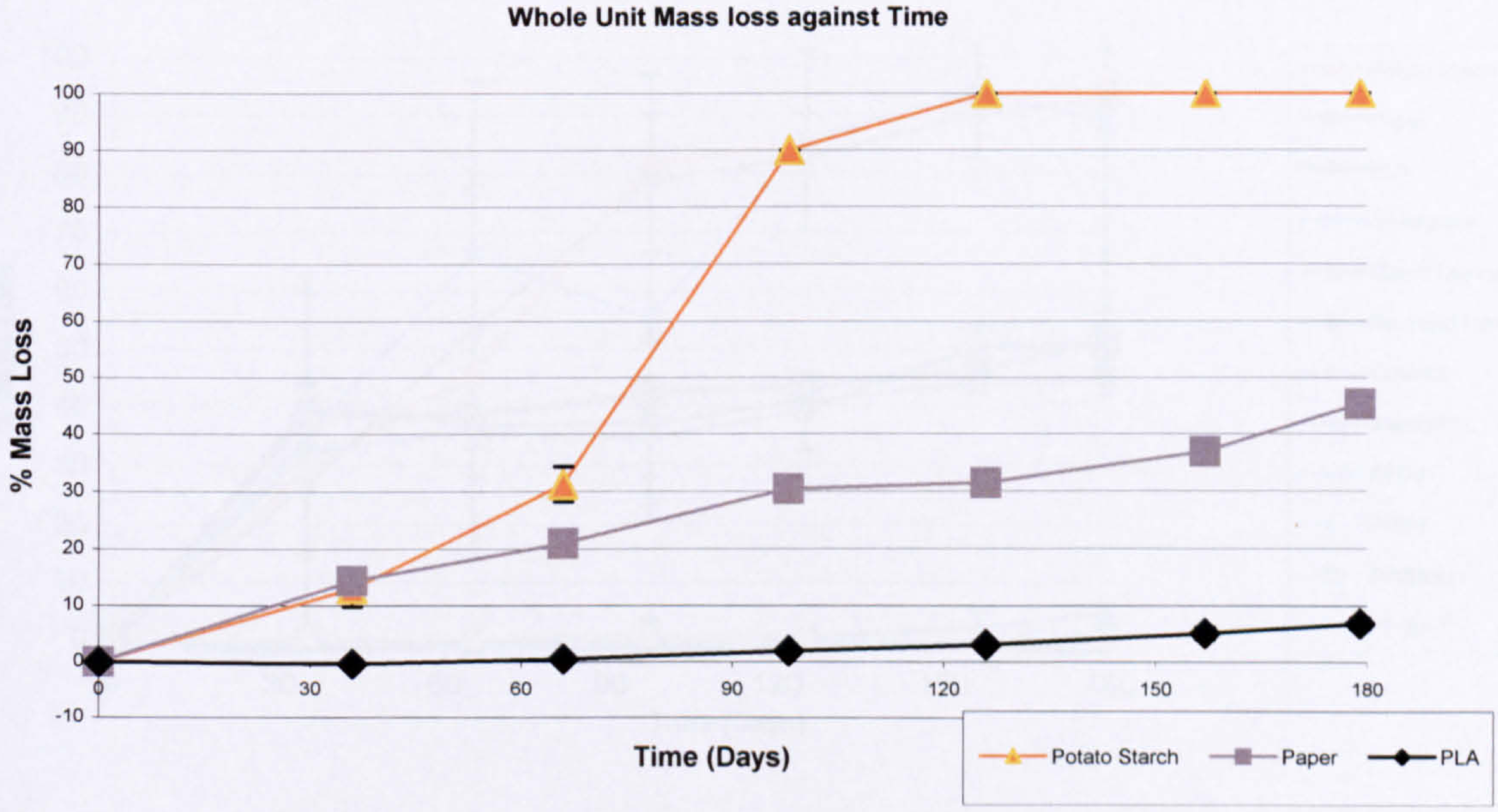


Figure 8.14: Whole Units mass loss (%) over time

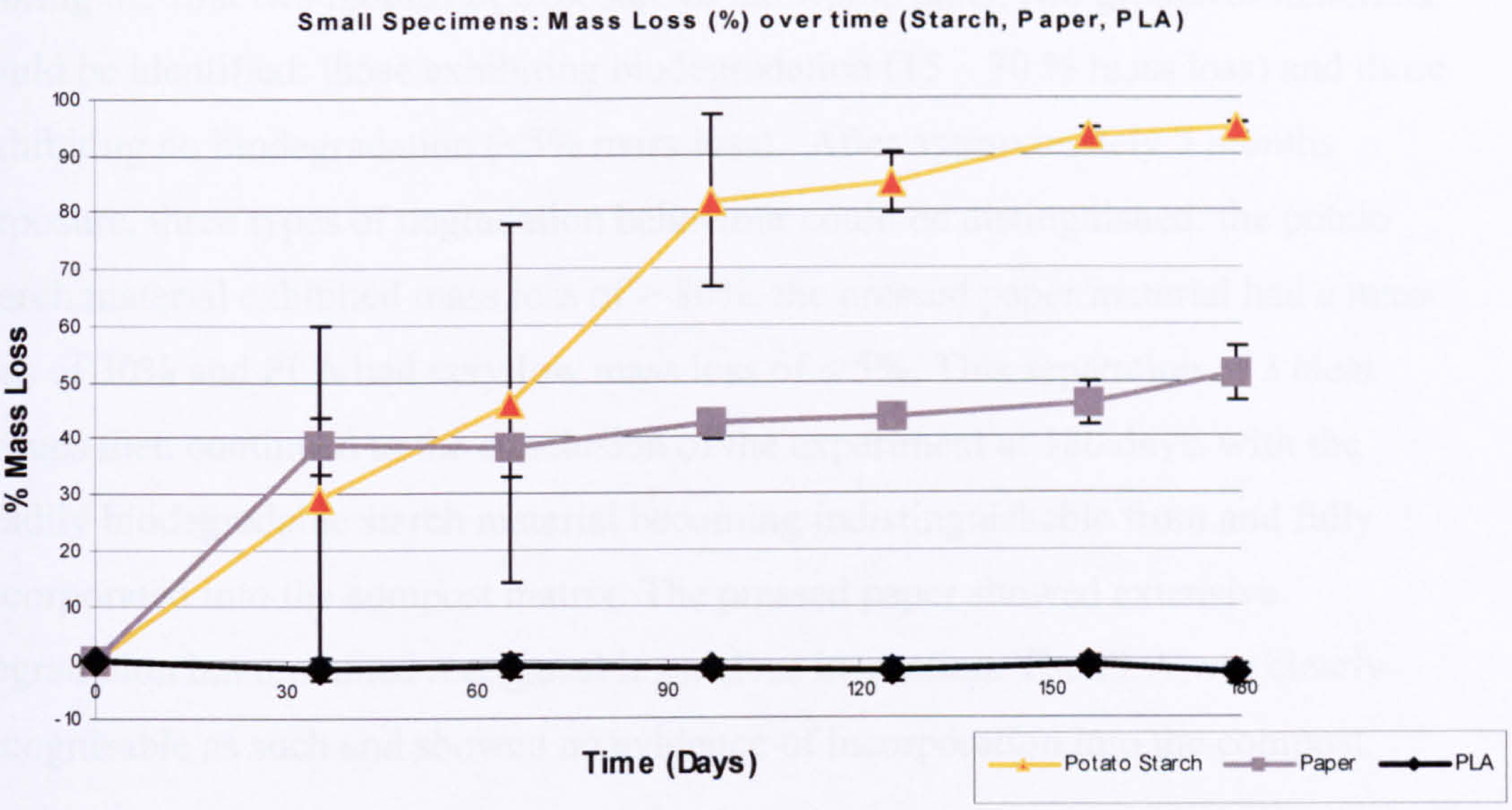


Figure 8.15: Small Specimens mass loss (%) over time (starch, paper, PLA)

The data for the full range of material types as small specimens are presented in Figure 8.16.

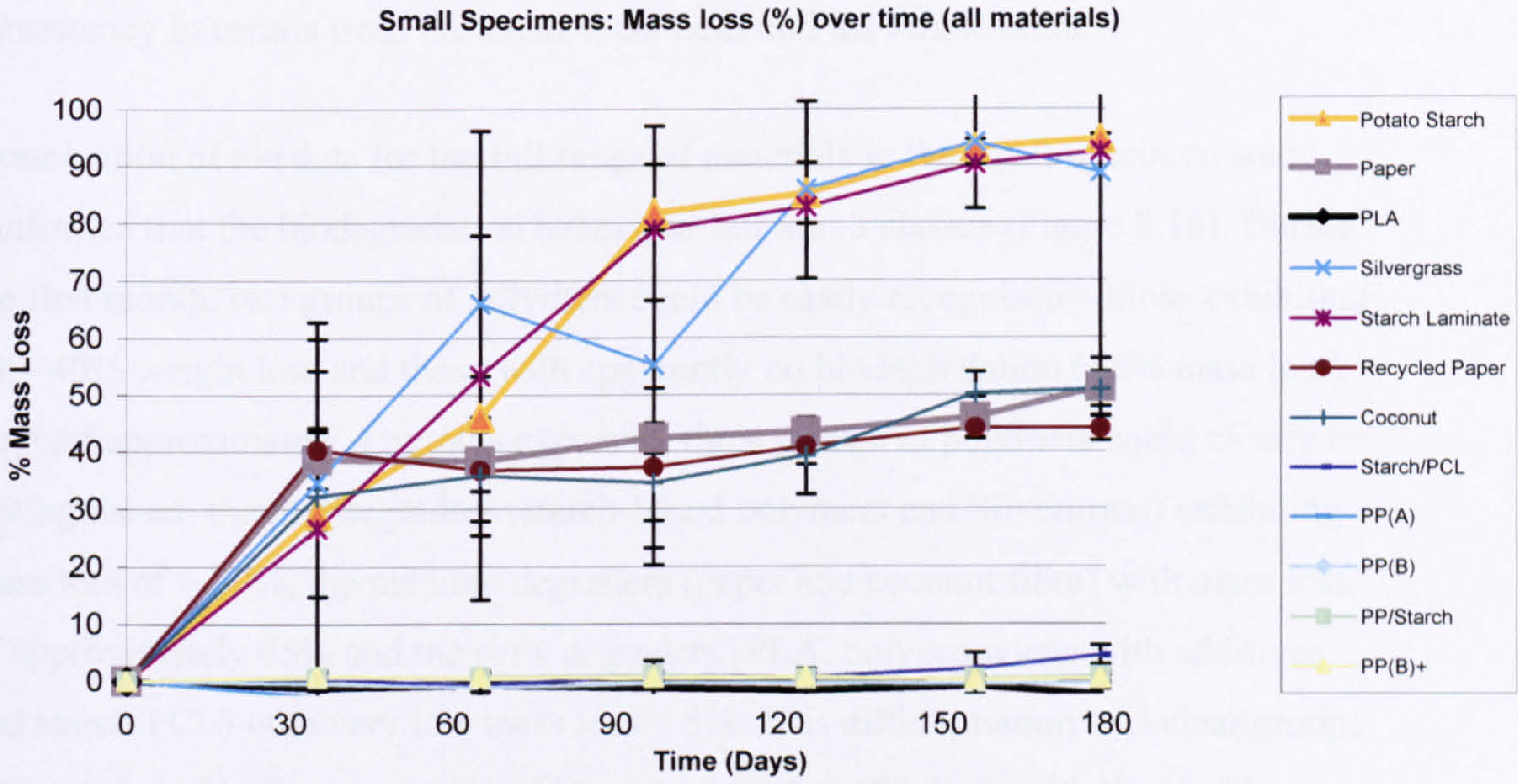


Figure 8.16: Small Specimens: mass loss (%) over time (all material types)

During the first two months of exposure of the whole units, two groups of materials could be identified: those exhibiting biodegradation (15 – 30 % mass loss) and those exhibiting no biodegradation (<5% mass loss). After approximately 3 months exposure, three types of degradation behaviour could be distinguished: the potato starch material exhibited mass loss of > 80%, the pressed paper material had a mass loss of 30% and PLA had very low mass loss of < 5%. This separation of 3 clear groups then continued to the conclusion of the experiment at 180 days, with the readily biodegradable starch material becoming indistinguishable from and fully incorporated into the compost matrix. The pressed paper showed extensive degradation but remained recognisable on close inspection. The PLA was clearly recognisable as such and showed no evidence of incorporation into the compost.

The experiment was also conducted using small specimens of the same materials and very similar results observed with 3 'classes' of behaviour (Figure 8.15). In this case, absolute levels of degradation in the starch material were initially slightly higher than with the whole unit although final levels of biodegradation were slightly lower than in the whole unit study. Paper showed a more rapid initial breakdown and PLA exhibited less breakdown than with the whole units (the whole units of PLA were probably mechanically damaged in the whole unit study). Overall there was a high degree of consistency in results from the small specimens and the whole units.

Examination of the data for the full range of materials in the small specimen study confirmed that the biodegradation behaviour fell into 3 classes (Figure 8.16). During the first month, two groups of polymers could be easily recognised – those exhibiting 30 – 40% weight loss and those with apparently no biodegradation (<5% mass loss). Beyond approximately 4 months exposure, three groups of polymers could clearly be distinguished: the fast degraders (starch-based polymers and Silvergrass) exhibiting mass loss of > 80%, the medium degraders (paper and coconut fibre) with mass loss of approximately 45% and the slow degraders (PLA, polypropylene with additives and starch/PCL) with very low mass loss < 5%. This differentiation of 3 clear groups then continued to the conclusion of the experiment at 180 days, with the readily degradable materials becoming indistinguishable from their sealed packets. The middle group showed extensive degradation but remained recognisable on close inspection. The slow degrading materials were clearly recognisable as such and showed little or no degradation.

The results for moisture content assessment (Figures 8.17 & 8.18, Table 8.4) showed that fast and medium rate degraders absorbed moisture readily during the composting process (range from 50 to 400% mc over the measurable time period). The slow degrader group exhibited very low levels of moisture absorption (typically < 40% mc and in the case of PLA <5% mc).

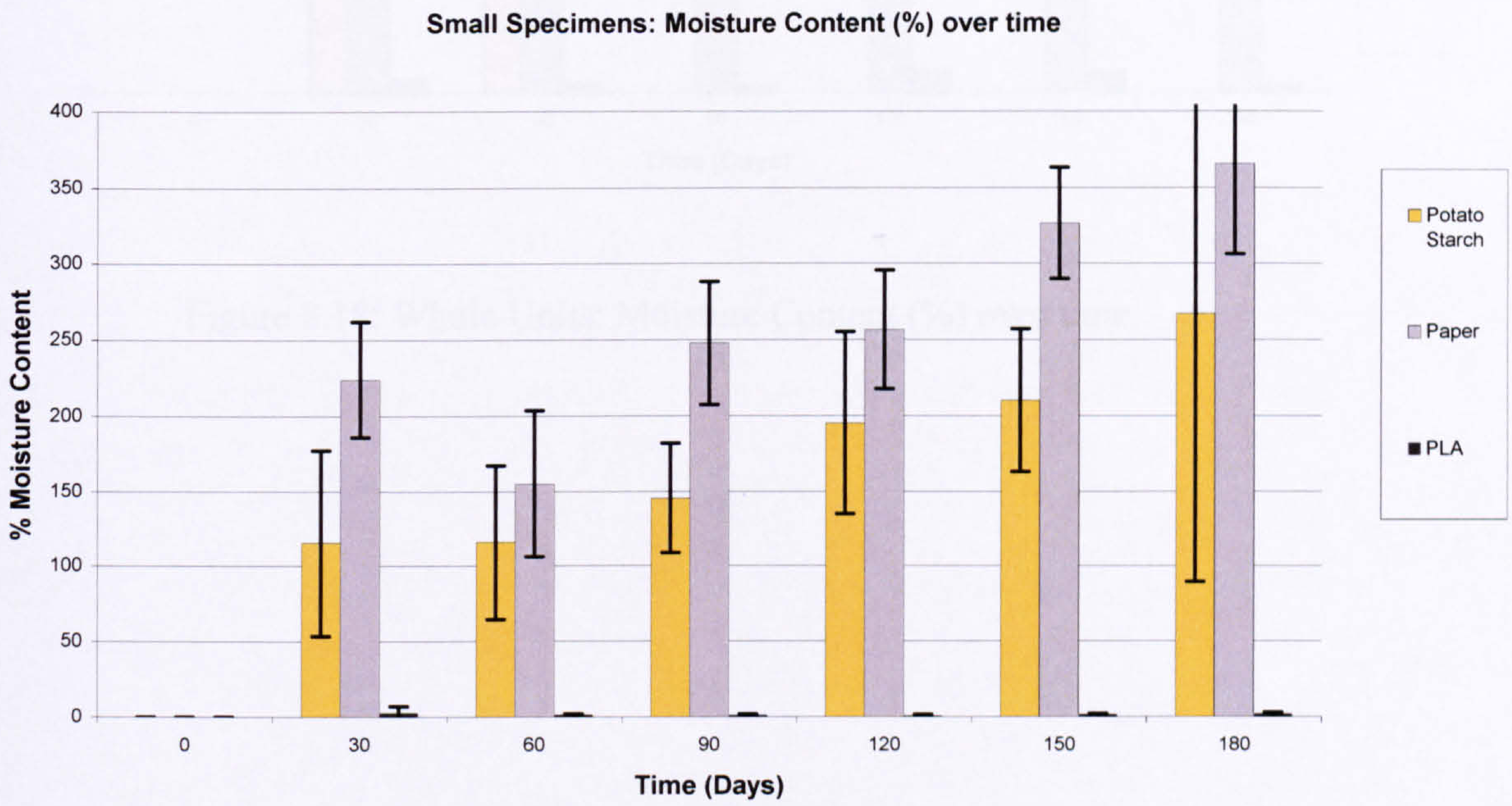


Figure 8.17: Small Specimens: Moisture Content (%) over time

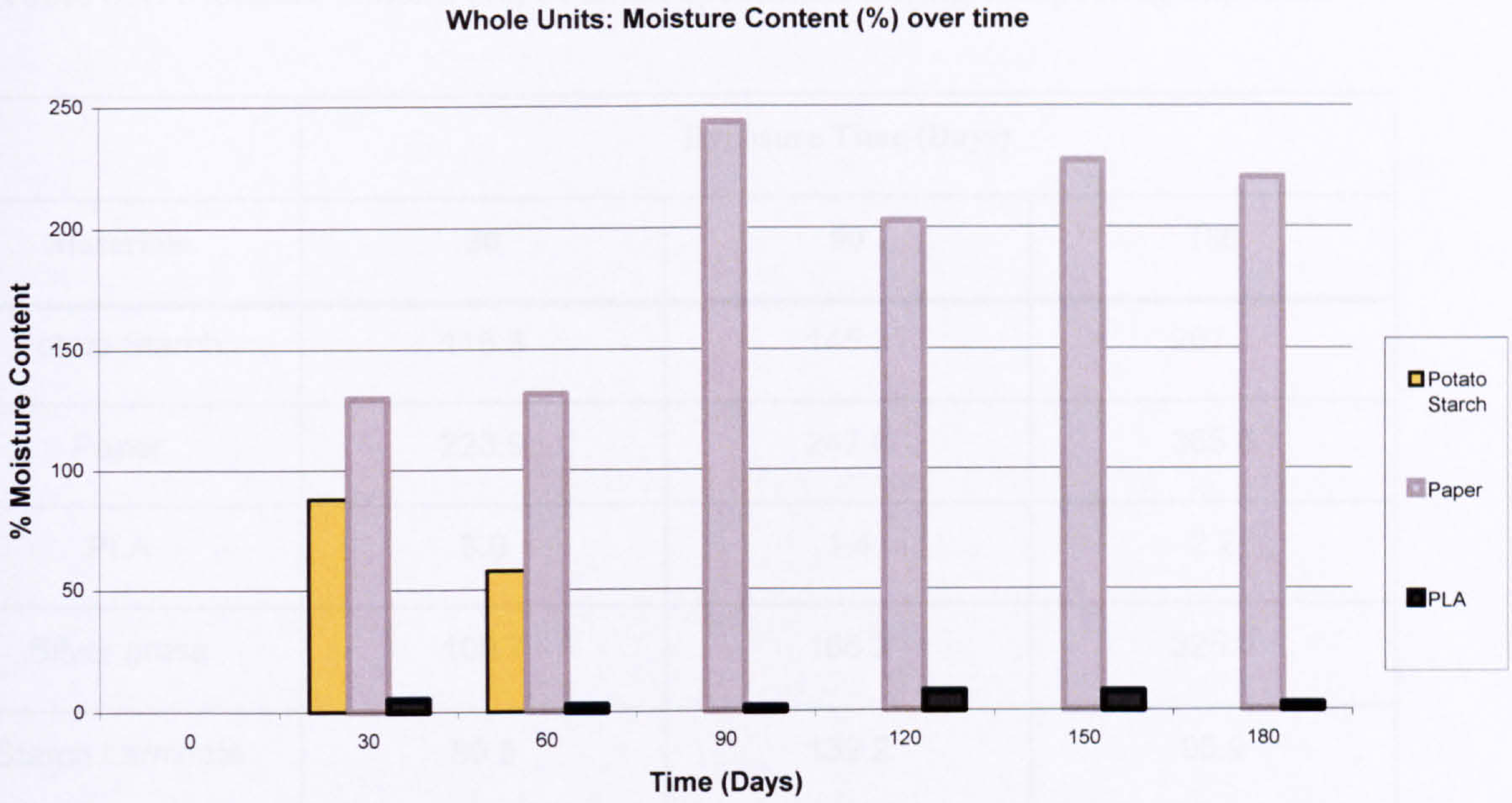


Figure 8.18: Whole Units: Moisture Content (%) over time

Table 8.4: Moisture content (%) of small specimens during composting exposure

	Exposure Time (Days)		
Materials	**30**	**90**	**180**
Potato Starch	115.3	145.3	267.1
Paper	223.9	247.8	365.6
PLA	3.0	1.4	2.2
Silver grass	100.7	166.2	325.0
Starch Laminate	80.5	132.2	90.9
Recycled Paper	229.9	196.1	349.1
Coconut	97.7	126.9	337.5
Starch/PCL	1.2	1.7	8.9
PP(A)	1.0	0.5	1.2
PP(B)	0.3	0.0	0.9
PP/Starch	6.9	9.1	11.6
PP(B)+	0.3	0.1	0.7

8.6.2 PAS 100 Seed Germination of Final Composts Results

The results of the PAS 100 bioassay (Table 8.5) show that all composts from the whole units (starch, paper and PLA) compost bins and from the composted base mix (control) gave equal or higher seed germination results compared to the growth medium base (PRGM). Furthermore all the 'amended' composts, with the exception of Bin 1 of PLA, gave equivalent or better fresh seedling masses (a 20% reduction in above ground seedling fresh mass relative to the PRGM control result. PLA Bin 1 had a 21% reduction in above ground seedling mass). All the amended composts failed the weed criterion of PAS 100, but this is expected because low temperature composting systems do not achieve sterilisation of weed seeds.

Table 8.5: Results of PAS 100 seed germination and seedling development study

Material	Compost Bin	Total No. of weeds per litre of compost	Total fresh mass of seedlings at 28 days	Av. fresh mass of seedlings at 28 days	Total no. of germinated seedlings at 7 days	Total no. of germinated seedlings at 14 days	Total no. of germinated seedlings at 28 days	Germinated seedlings as a % of control seedlings at 14 days	Germinated seedlings as a % of control seedlings at 28 days
		(No/l.)	(g)	(g)	(No.)	(No.)	(No.)	(%)	(%)
Starch	Bin 1	36.0	49.9	1.7	29	30	30	120	120
	Bin 2	49.6	47.1	1.7	29	28	28	112	112
Paper	Bin 1	20.5	62.2	2.4	27	26	26	104	104
	Bin 2	56.3	48.6	1.9	26	27	25	108	100
PLA	Bin 1	29.3	38.0	1.4	28	27	28	108	112
	Bin 2	98.7	42.5	1.5	27	28	28	112	112
Control	Bin 1	105.0	45.0	1.6	27	28	28	112	112
	Bin 2	74.4	55.7	2.1	26	27	27	108	108
PRGM Control		1.5	48.1	1.9	25	25	25	100	100

Table 8.5 (continued): Extra columns of the results of PAS 100 seed germination and seedling development study

Material	Compost Bin	Visible abnormalities	Additional factors affecting results
Starch	Bin 1	1 bent stem	All watered 3 times per week with deionised water
	Bin 2	1 recent germination/ stunted	All large weeds removed after counting & a cumulative value has been recorded
Paper	Bin 1	1 bent stem, 2 stunted/ recent germinations	Trays turned through 180 degrees 2/ 3 times per week
	Bin 2	1 recent germinated seedling	
PLA	Bin 1	Seedlings fell over easily, 2 recent germinations	
	Bin 2	1 stunted, 1 bent stem	
Control	Bin 1	1 Coprinus mushroom	
	Bin 2	Compost dry at final harvesting	
PRGM Control		1 seedling aborted, very stunted growth	

The results of the PAS 100 bioassay show that when comparing the average fresh masses of the PRGM control at 28 days with the trial composts there is inconsistency in the results across the two test bins. The Pactiv, Potato Pack and Experimental Control results of the average fresh mass are higher than that of the PRGM control. However, the PLA result is 16.4% lower than the PRGM control. This is still above the desired threshold.

All the germination seedling results, as a percentage of the control seedlings at 7, 14 and 28 days, are above the PRGM control, resulting in a pass of the PAS 100 standard.

The bioassay indicates that the composting process has not been effective at eradicating weed and seed contamination, and the test would fail the PAS 100 standard on weeds. This test is however, not suggested for domestic composter and any such compost would not pass this weed test. The presence of any sample material is therefore not considered to be the reason for the failure on weed suppression.

8.6.3 Laboratory Scale Compost Experiment One and Two Results

This sub-section presents the results of both laboratory scale compost experiments.

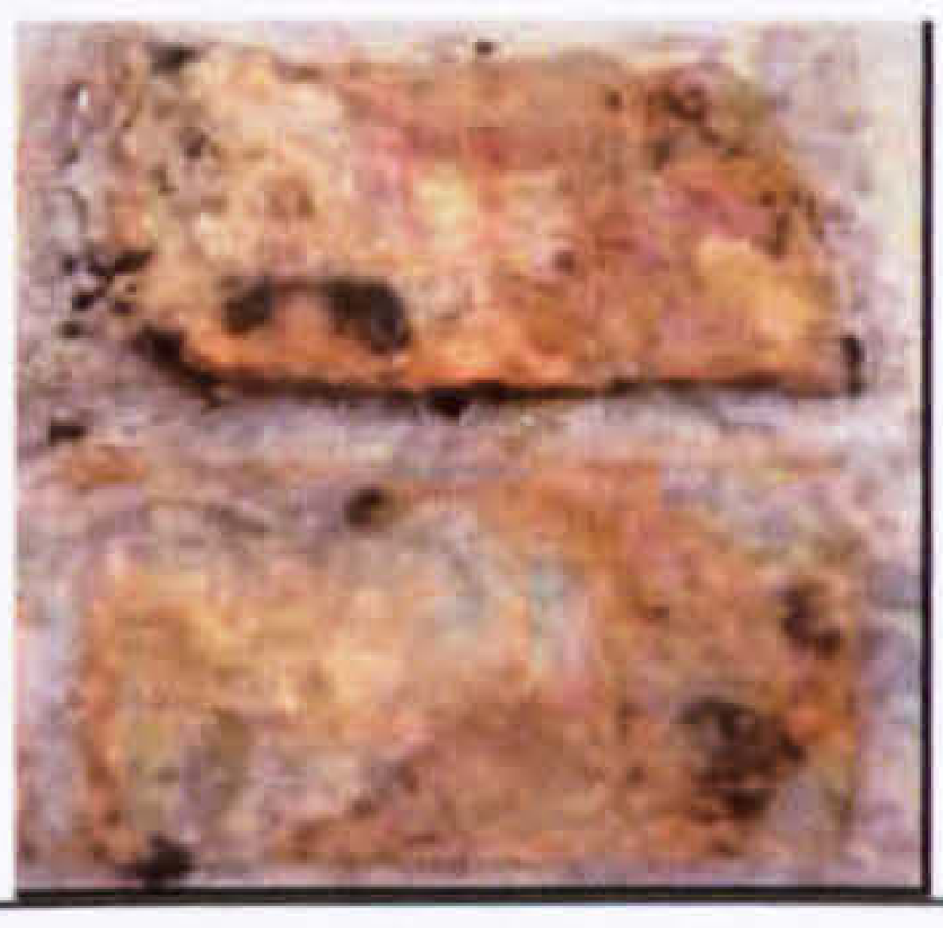
8.6.3.1 Visual Assessment of the Laboratory Scale Composters

The temperature profile of the laboratory scale composters was kept to a constant 25°C in the incubators throughout the composting period of both laboratory-based experiments.

The results of the visual assessment are summarised in table 8.6. In general the breakdown of lab 1 specimens was very similar to that of lab 2 specimens.

Table 8.6: Visual assessment of packaging materials during simulated home composting

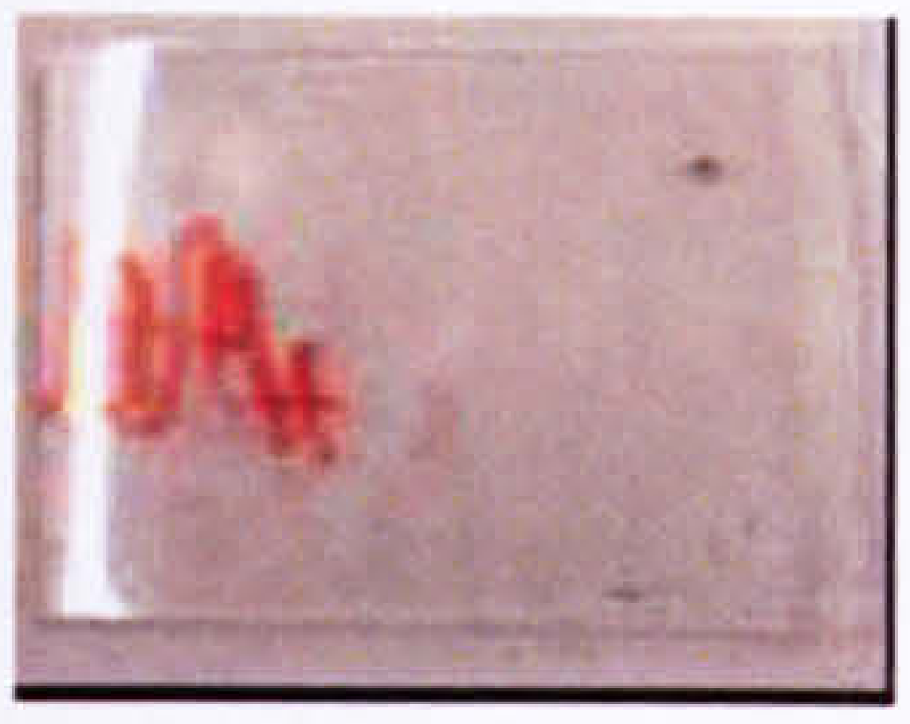
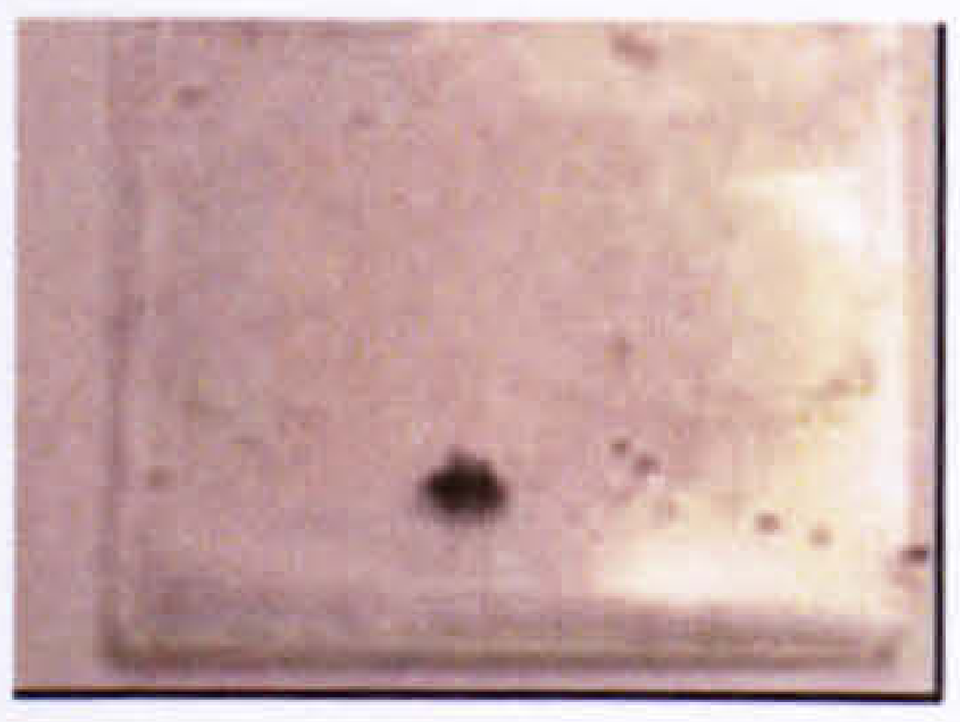
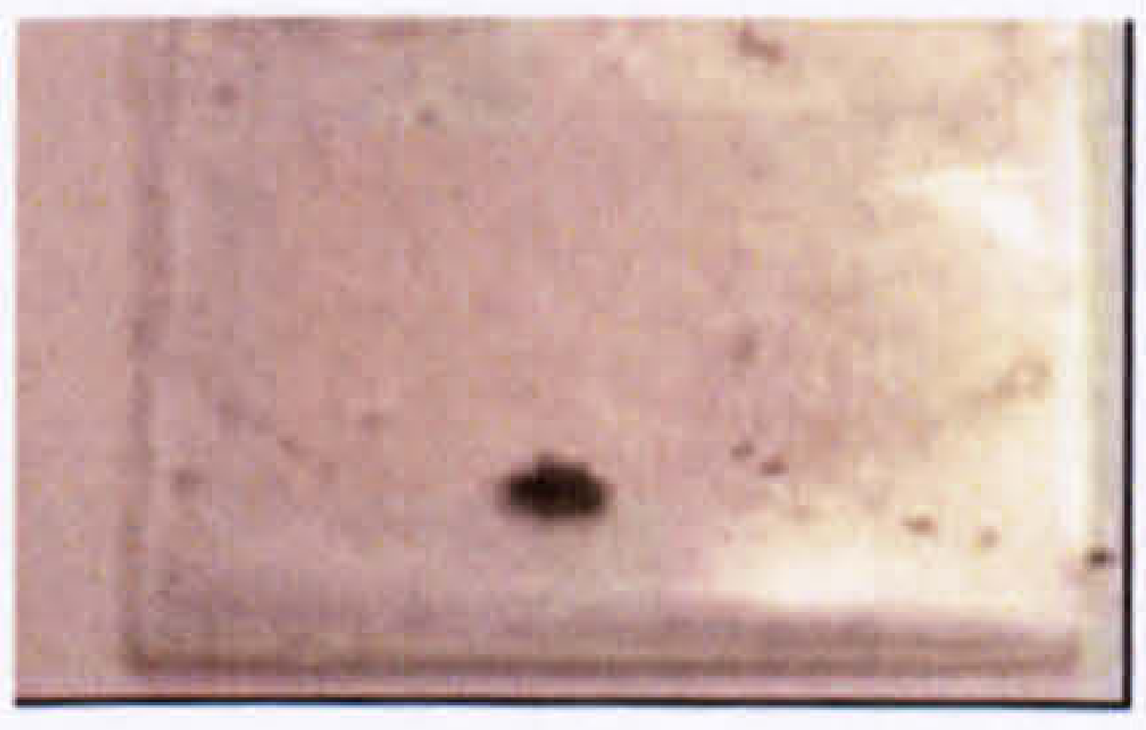
Potato starch tray

No. of days	Lab1 Image	Description	No. of days	Lab2 Image	Description
0		Original sample	0		Original sample
3		Small amount of degradation on sample	10		Obvious signs of degradation on sample
6		Sample is degrading and is wet to touch	20		Sample has degraded parts remain.
10		Sample has degraded and small remains can be obtained.	32		Sample has degraded and small remains can be obtained.
12		Sample has degraded and small remains can be obtained.	39		Sample has degraded and small remains can be obtained.
18		Very small amounts of sample left.	50		Very small amounts of sample left.
26		Very small amounts of sample left.	60		Very small amounts of sample left.

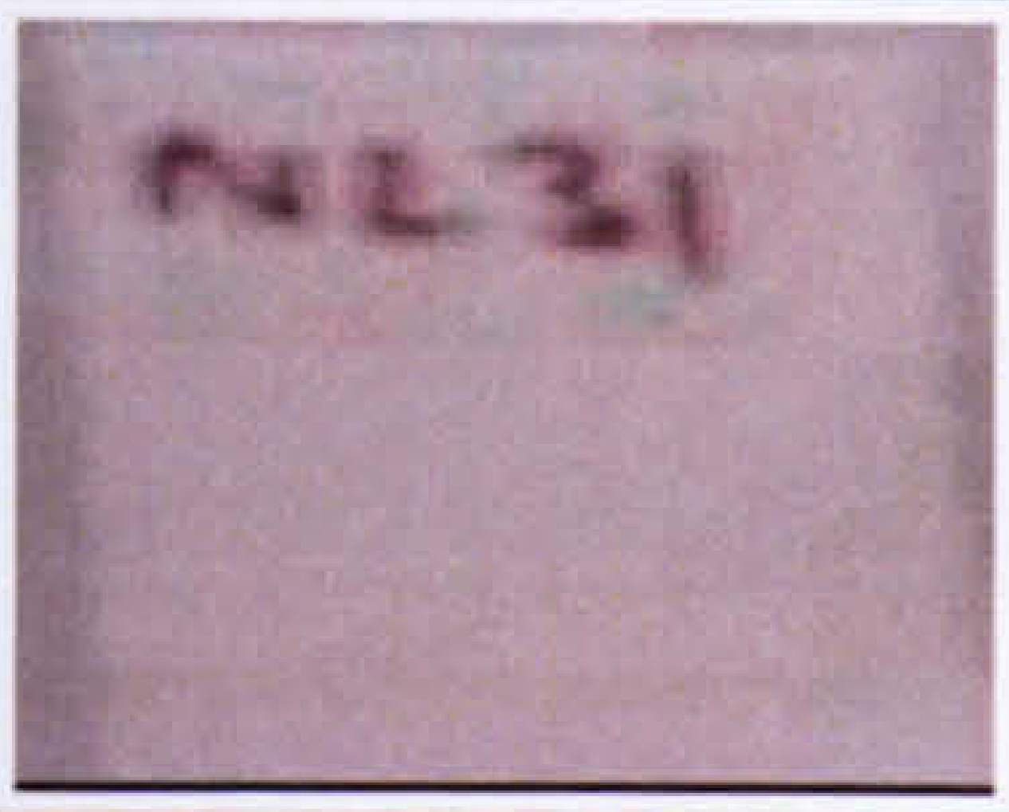
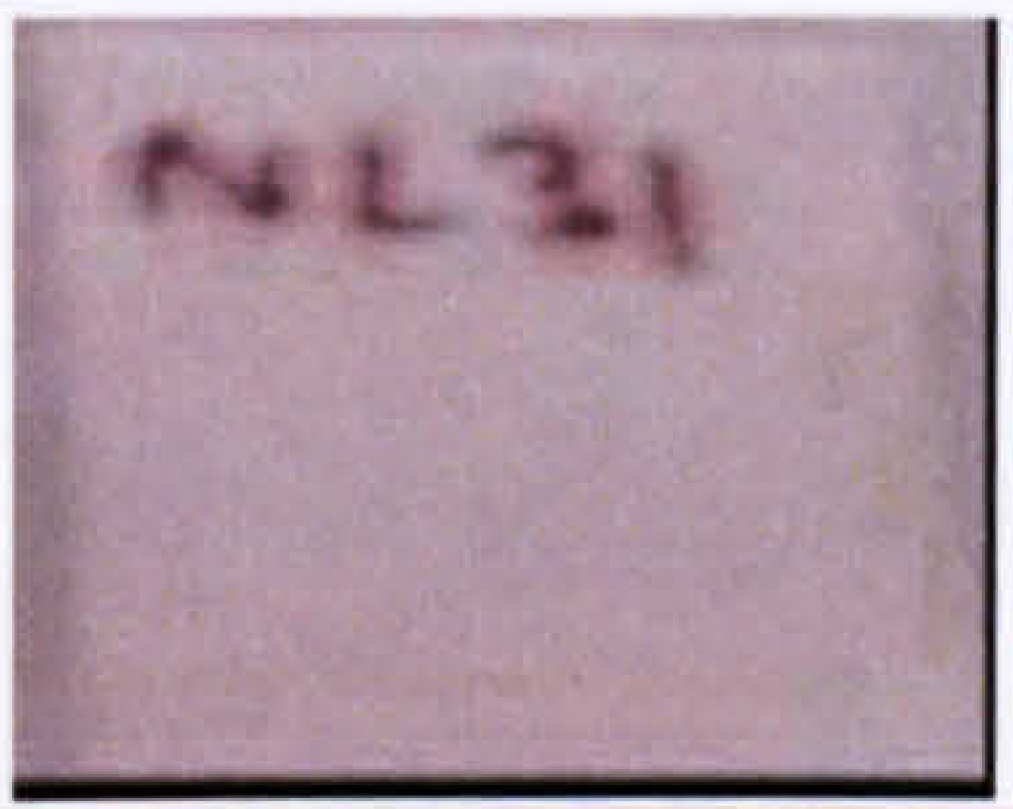
Pressed wood pulp paper plate

No. of days	Lab 1 Image	Description	No. of days	Lab 2 Image	Description
0		Tray in its original state.	0		Tray in its original state.
3		Sample shows signs of wetting.	10		Sample has a large amount of mould growth
6		Sample has mould growth	20		Sample has a large amount of mould growth
10		Sample has more mould growth and shows signs of wetting	32		Obvious signs of degradation, sample has lots of mould growth.
12		Sample has a large amount of mould growth	39		Further signs of degradation and the sample is breaking up.
18		Sample has a large amount of mould growth	50		Obvious signs of degradation, sample has lots of mould growth.
26		Sample has a large amount of mould growth	60		Sample is breaking up. Lots of mould growth

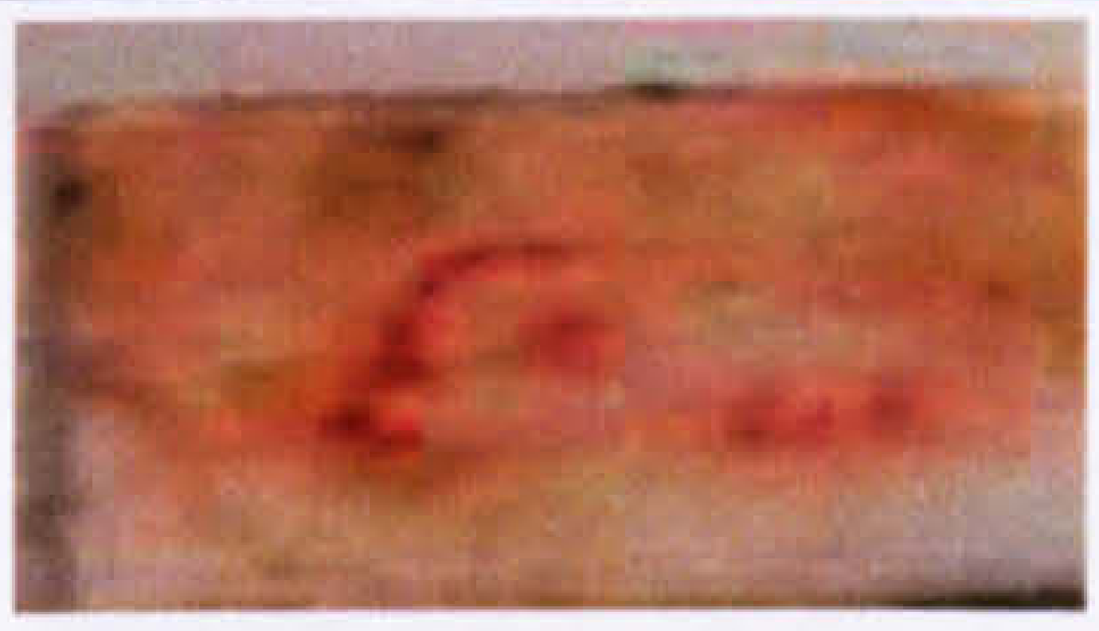
PLA tray/ film

No. of days	Lab 1	Description lab 1	No. of days	Lab 2	Description lab 2
0		Tray in its original state	0		Tray in its original state
3		No Degradation observed, samples intact, no mould growth, no free water	10		No Degradation observed, samples intact, no mould growth, no free water
6		No Degradation observed, samples intact, no mould growth, no free water	20		No Degradation observed, samples intact, no mould growth, no free water
10		No Degradation observed, samples intact, no mould growth, no free water	32		No Degradation observed, samples intact, no mould growth, no free water
12		No Degradation observed, samples intact, no mould growth, no free water	39		No Degradation observed, samples intact, no mould growth, no free water
18		No Degradation observed, samples intact, no mould growth, small amount of free water	50		No Degradation observed, samples intact, no mould growth, small amount of free water
26		No Degradation observed, samples intact, no mould growth, no free water	60		No Degradation observed, samples intact, no mould growth, no free water

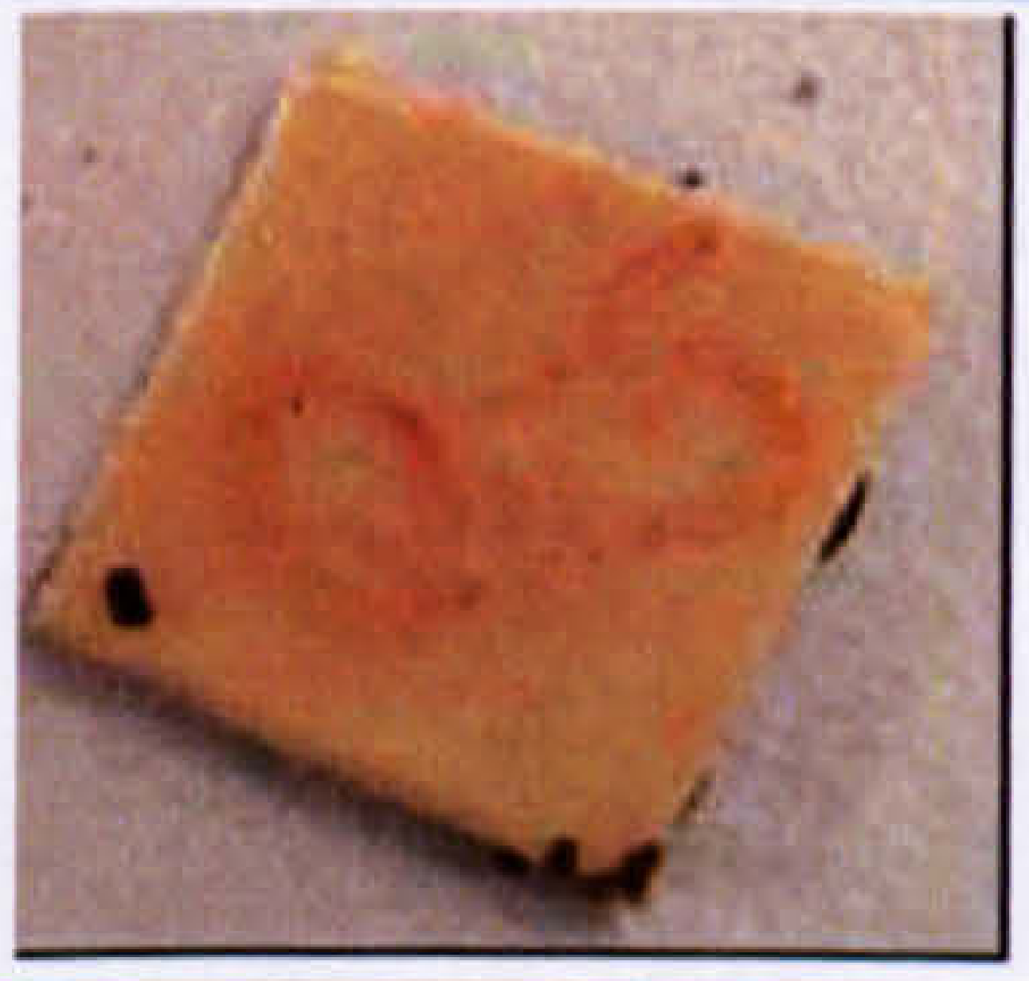
N Silvergrass

No. of days	Lab 1 Image	Description	No. of days	Lab 2 Image	Description
0		Sample in original state.	0		Sample in original state.
3		Sample dry and now mould growth.	10		Sample shows signs of wetting.
6		Some moisture absorption. Very little mould growth	20		Total mould growth. Sample very fragile.
10		Particles adhering themselves to the sample. Sample shows signs of wetting. Some mould growth observed	32		Very small amounts of sample left.
12		Particles adhering themselves to the sample. Sample is wet. Mould growth observed	39		Very small amounts of sample left.
18		Lots of mould growth. Sample breaking up	50		Very small amounts of sample left.
26		Total mould growth. Sample very fragile.	60		Very small amounts of sample left.

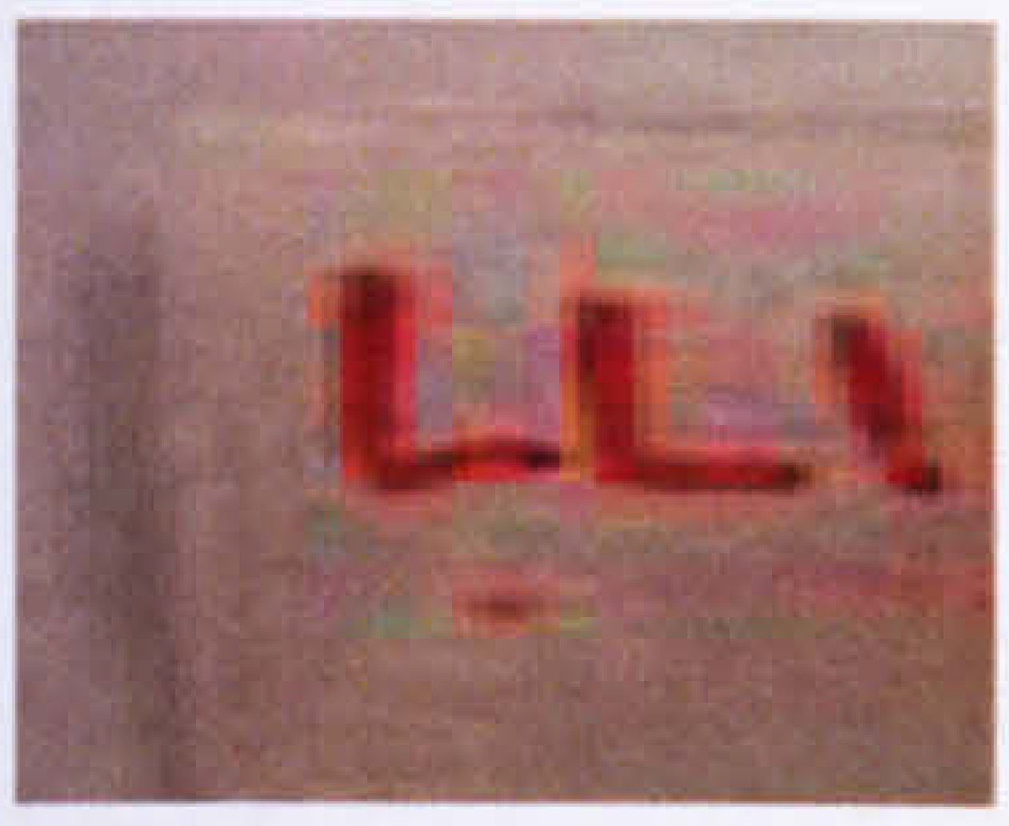
Materbi film (Starch/PCL)

No. of days	Lab 1	Lab1Description	No. of days	Lab 2	Lab1Description
0		Sample in its original state	0		A sample in its original state
3		No Degradation observed, samples intact, no mould growth, no free water	10		No Degradation observed, samples intact, no mould growth, no free water
6		No Degradation observed, samples intact, no mould growth, no free water	20		No Degradation observed, samples intact, no mould growth, no free water
10		No Degradation observed, samples intact, no mould growth, no free water	32		No Degradation observed, however signs of mould growth. Samples intact, no free water
12		No Degradation observed, samples intact, no mould growth, no free water	39		No Degradation observed, however increased signs of mould growth. Samples intact, no free water
18		No Degradation Slight mould growth	50		No Degradation observed, however increased signs of mould growth. Samples intact, no free water
26		No Degradation Slight mould growth	60		No Degradation observed, however increased signs of mould growth. Samples intact, no free water

Q Polypropylene with additive B+

No. of days	Lab 1 Image	Description	No. of days	Lab 2 Image	Description
0		Sample in original state.	0		Sample in original state.
3		No Degradation observed, samples intact, no mould growth, no free water	10		No Degradation observed, samples intact, no mould growth, no free water
6		No Degradation observed, samples intact, no mould growth, no free water	20		No Degradation observed, samples intact, no mould growth, no free water
10		No Degradation observed, samples intact, no mould growth, no free water	32		No Degradation observed, samples intact, no mould growth, no free water
12		No Degradation observed, samples intact, no mould growth, no free water	39		No Degradation observed, samples intact, no mould growth, no free water
18		No Degradation observed, samples intact, no mould growth, no free water	50		No Degradation observed, samples intact, no mould growth, no free water
26		No Degradation observed, samples intact, no mould growth, no free water	60		No Degradation observed, samples intact, no mould growth, no free water

L PP/Starch

No. of days	Lab 1 Image	Description	No. of days	Lab 2 Image	Description
0		Sample in original state.	0		Sample in original state.
3		No Degradation observed, samples intact, no mould growth, no free water	10		No Degradation observed, samples intact, no mould growth, no free water
6		No Degradation observed, samples intact, no mould growth, no free water	20		No Degradation observed, samples intact, no mould growth, no free water
10		No Degradation observed, samples intact, no mould growth, no free water	32		No Degradation observed, samples intact, no mould growth, no free water
12		No Degradation observed, samples intact, no mould growth, no free water	39		No Degradation observed, samples intact, no mould growth, no free water
18		No Degradation observed, samples intact, no mould growth, no free water	50		No Degradation observed, samples intact, little mould growth, no free water
26		No Degradation observed, samples intact, no mould growth, no free water	60		No Degradation observed, samples intact, no mould growth, no free water

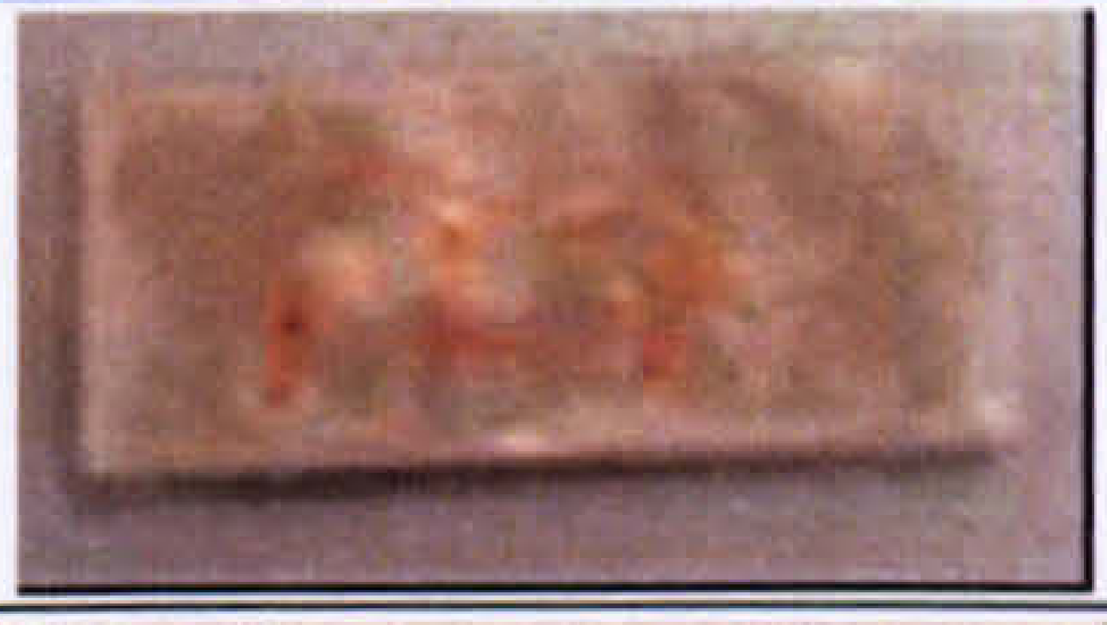
S Novel Starch 1

No. of days	Lab 1 Image	Description	No. of days	Lab 2 Image	Description
0		Sample in original state.	0		Sample in original state.
3		Particles adhering themselves to the sample. Sample shows signs of wetting. Some mould growth observed	10		Sample degrading and breaking up into small fragments. Some mould growth observed
6		Sample degrading and breaking up into small fragments. Some mould growth observed	20		Very small amounts of sample left.
10		Sample degrading and breaking up into small fragments. Mould growth observed	32		Very small amounts of sample left.
12		Very small amounts of sample left.	39		Very small amounts of sample left.
18		Very small amounts of sample left.	50		Very small amounts of sample left.
26		Very small amounts of sample left.	60		Very small amounts of sample left.

Starch/ Materbi

No. of days	Lab 1 Image	Description
0		Tray in original state.
3		Sample shows signs of wetting.
6		Some degradation observed, film coating still intact.
10		Some degradation observed, mould growth. However film remains intact
12		Obvious signs of degradation, mould growth. However film remains intact
18		Obvious signs of degradation, sample has broken into bits, lots of mould growth. However film remains intact
26		Sample has largely degraded with the exception of the Materbi coating

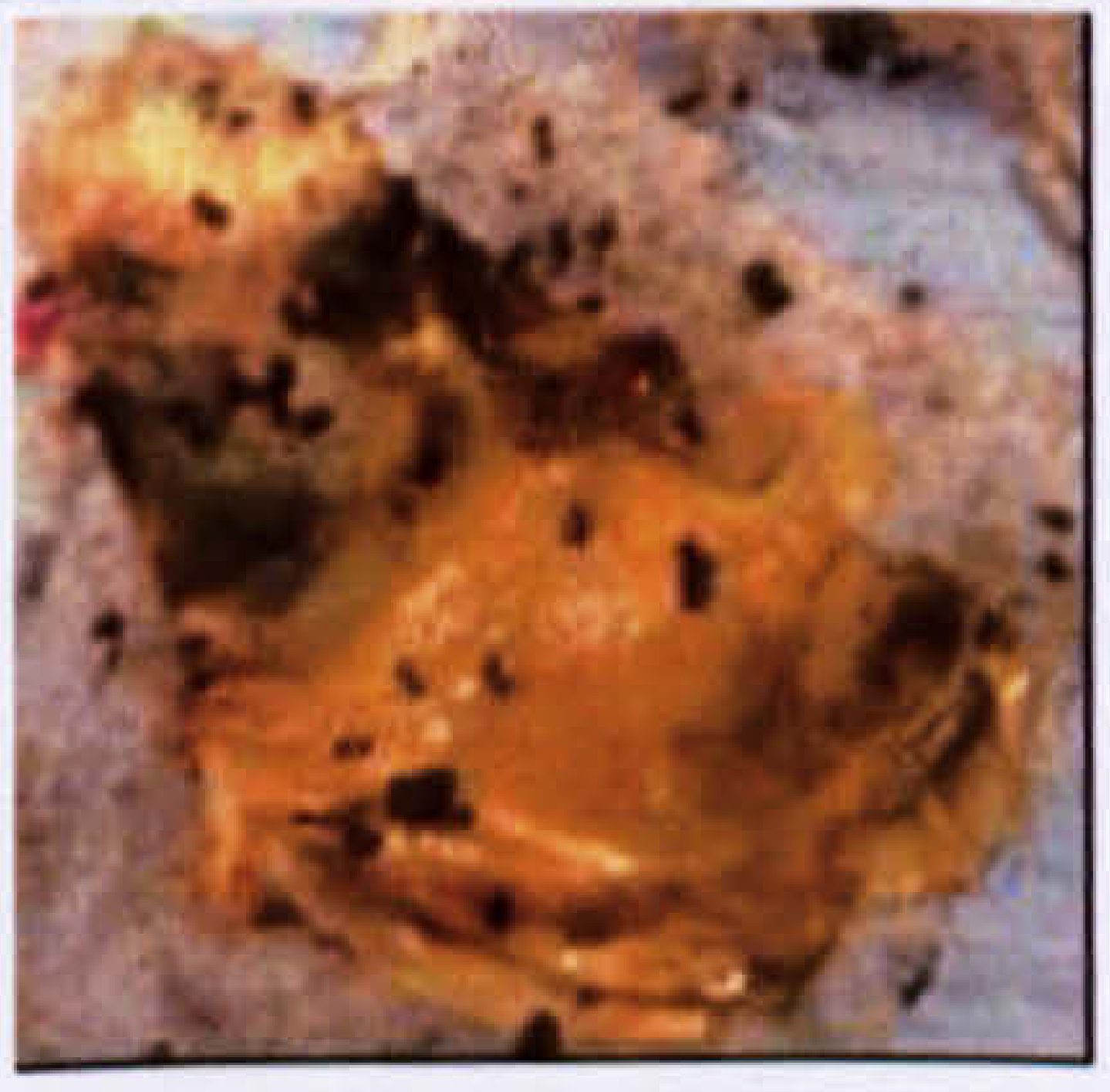
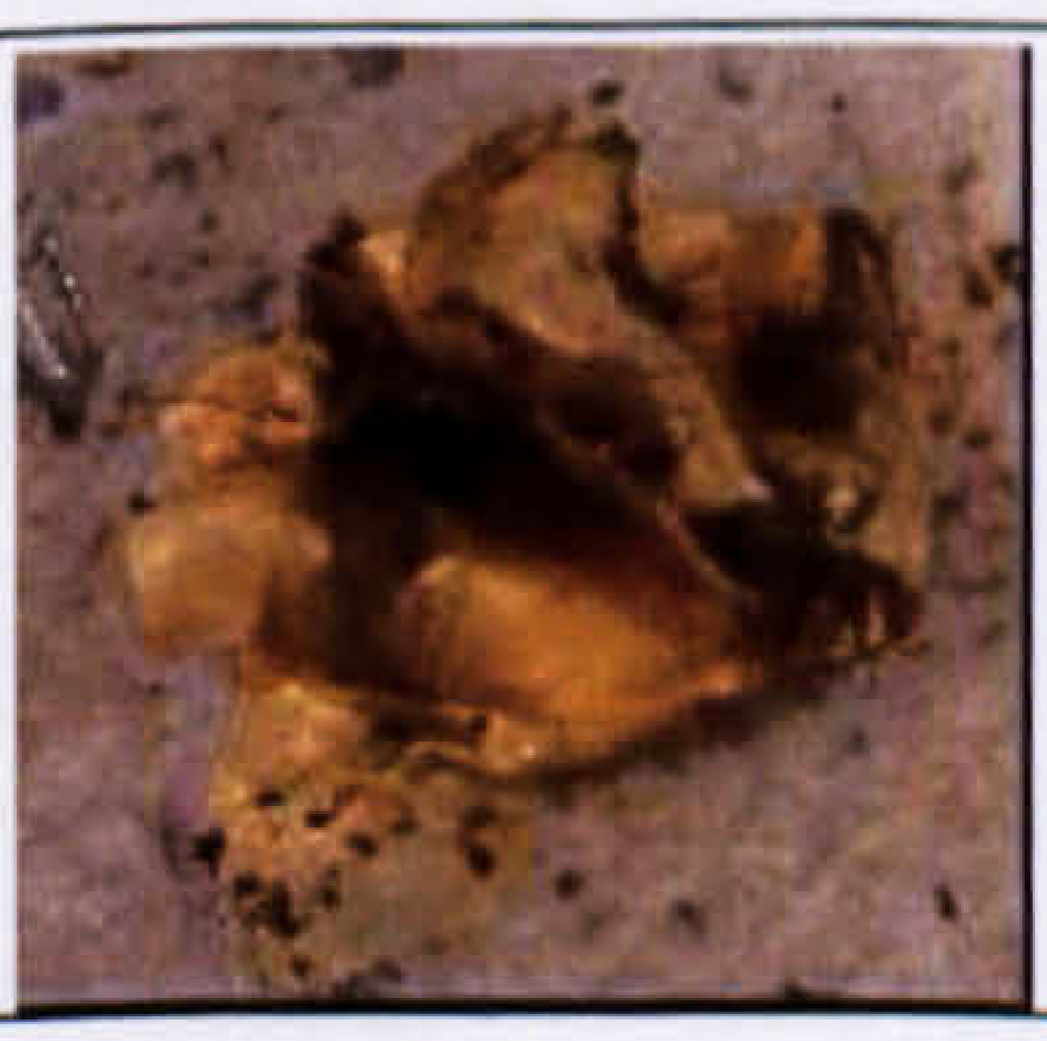
F Polypropylene with Additive A

No. of days	Lab 1 Image	Description
0		Sample in original state.
3		No Degradation observed, samples intact, no mould growth, no free water
6		No Degradation observed, samples intact, no mould growth, no free water
10		No Degradation observed, samples intact, no mould growth, no free water
12		No Degradation observed, samples intact, no mould growth, no free water
18		No Degradation observed, samples intact, no mould growth, no free water
26		No Degradation observed, samples intact, no mould growth, no free water

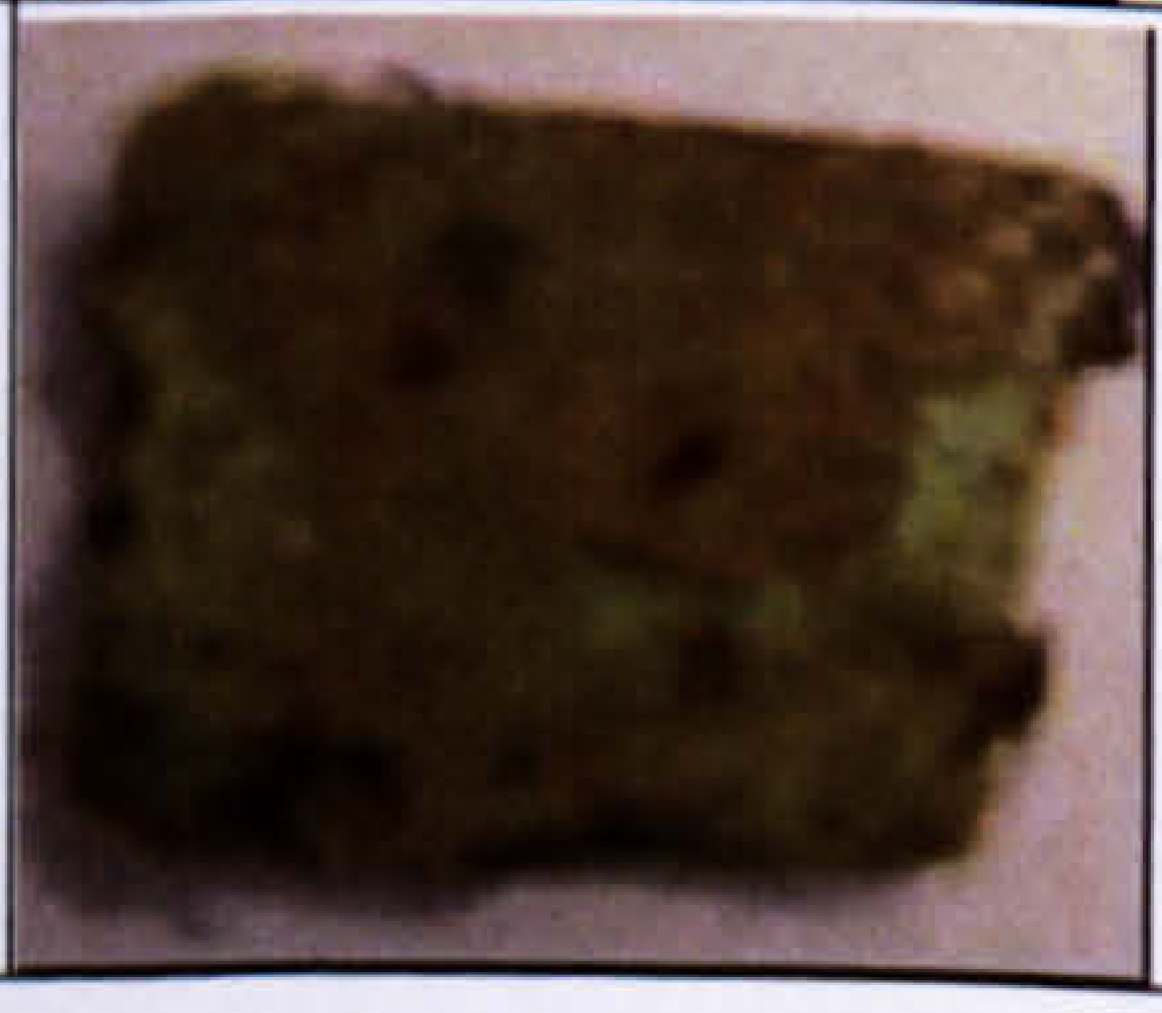
G Polypropylene with additive B

No. of days	Lab 1 Image	Description
0		Sample in original state.
3		No Degradation observed, samples intact, no mould growth, no free water.
6		No Degradation observed, samples intact, no mould growth, no free water
10		No Degradation observed, samples intact, no mould growth, no free water
12		No Degradation observed, samples intact, no mould growth, no free water
18		No Degradation observed, samples intact, no mould growth, no free water
26		No Degradation observed, samples intact, no mould growth, no free water

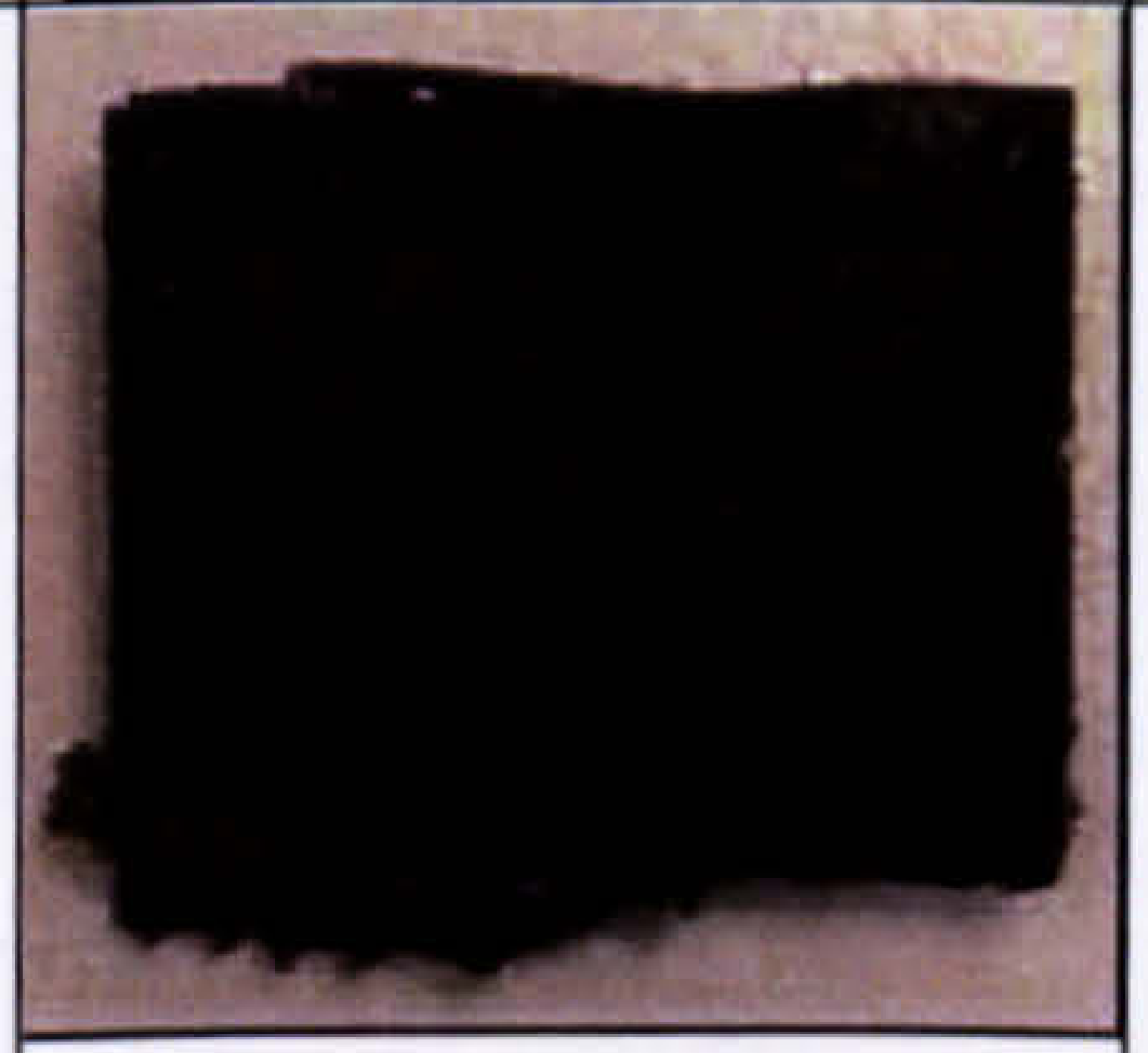
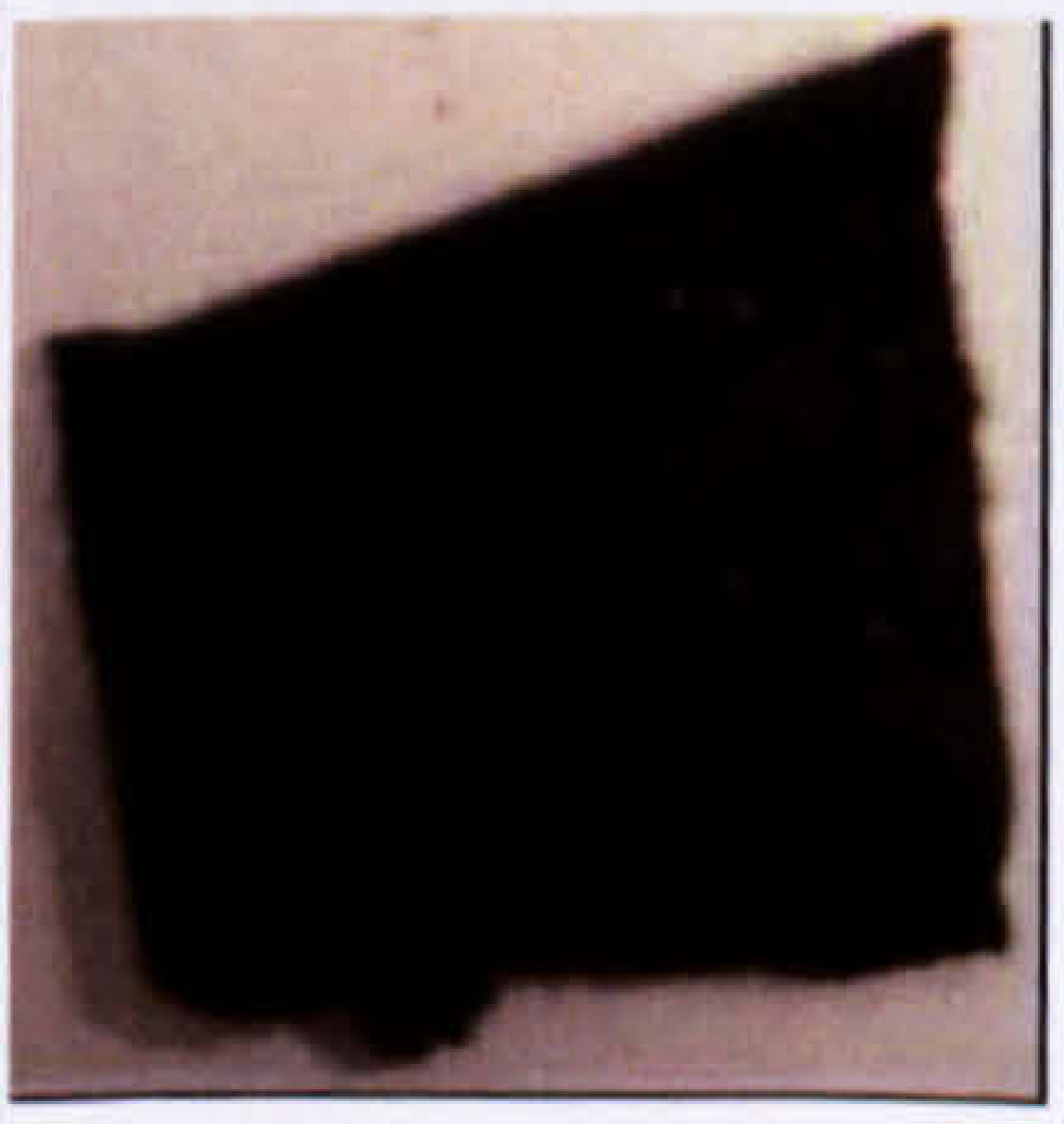
H Plantic

No. of days	Lab 1 Image	Description
0		Tray in its original state.
3		Particles adhering themselves to the sample. Sample shows signs of wetting.
6		Particles adhering themselves to the sample. Sample shows signs of wetting. Some mould growth observed
10		Particles adhering themselves to the sample. Mould growth observed, sample fragile
12		Mould growth observed, sample fragile.
18		Many particles adhering themselves to the sample. High degree of wetting. Lots mould growth observed
26		Many particles adhering themselves to the sample. High degree of wetting. High degree of mould growth observed

K Recycled Paper

No. of days	Lab 1 Image	Description
0		Tray in original state.
3		Sample shows signs of wetting.
6		Sample shows signs of wetting.
10		Sample shows signs of wetting
12		Sample shows signs of wetting.
18		Sample shows signs of wetting and some mould growth
26		Sample shows signs of wetting and a high degree of mould growth

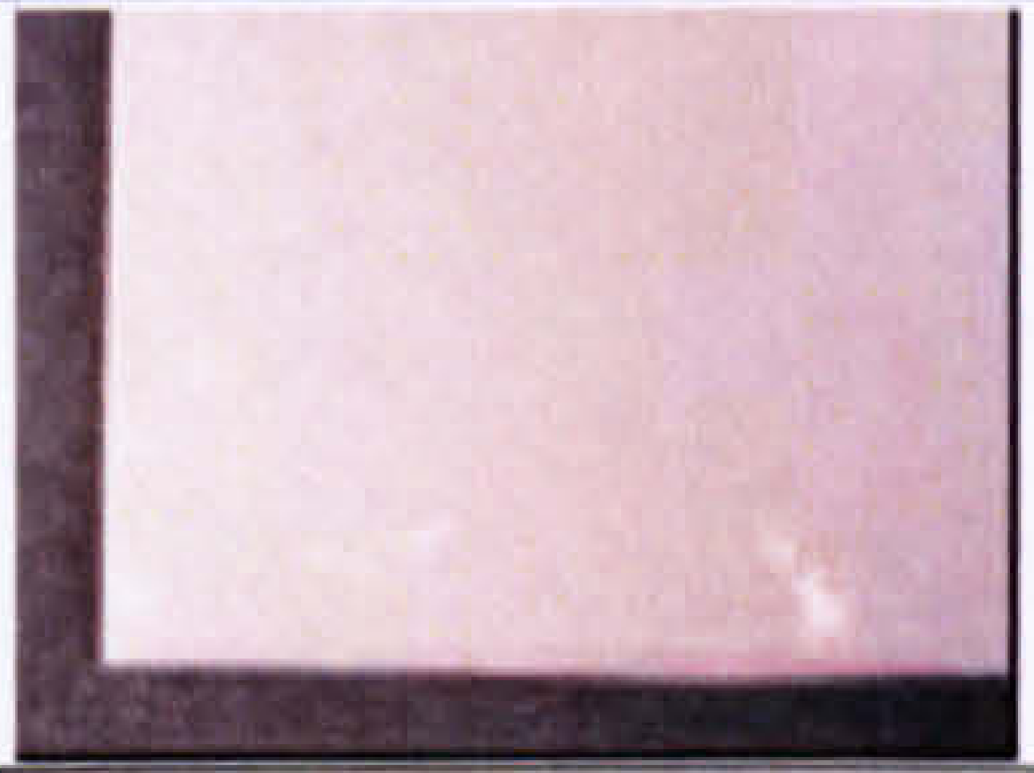
M Coconut

No. of days	Lab 1 Image	Description
0		Tray in original state.
3		No Degradation observed, samples intact, no mould growth, Sample shows signs of wetting.
6		No Degradation observed, samples intact, no mould growth, Sample shows signs of wetting
10		No Degradation observed, samples intact, no mould growth, Sample shows signs of wetting
12		No Degradation observed, samples intact, no mould growth, Sample shows signs of wetting..
18		No Degradation observed, samples intact, some mould growth, Sample shows signs of wetting.
26		No Degradation observed, samples intact, some mould growth, Sample shows signs of wetting.

T Novel Starch 2

No. of days	Lab 1 Image	Description
0		Sample in original state.
3		Sample shows signs of wetting.
6		Sample degrading and breaking up into small fragments. Some mould growth observed
10		Sample degrading and breaking up into small fragments. Mould growth observed
12		Very small amounts of sample left.
18		Very small amounts of sample left.
26		No sample left.

W Novel Starch 3

No. of days	Lab 1 Image	Description
0		Sample in original state.
3		Sample shows signs of wetting.
6		Sample degrading and breaking up into small fragments. Some mould growth observed
10		Sample degrading and breaking up into small fragments. Mould growth observed
12		Very small amounts of sample left.
18		Very small amounts of sample left.
26		No sample left.

X Novel Starch 4

No. of days	Lab 1 Image	Description
0		Sample in original state.
3		Sample shows signs of wetting.
6		Sample degrading and breaking up into small fragments. Some mould growth observed
10		Very small amounts of sample left.
12		Very small amounts of sample left.
18		Very small amounts of sample left.
26		No sample left.

Table 8.7: Alternative Table for Laboratory Experiment One

Property	Material	3	6	10	12	18	26
Moisture	Starch	**	**	***	****	****	****
	Paper	*	*	**	**	***	***
	PLA	-	-	-	-	-	-
	Silvergrass	*	*	**	**	***	***
	Starch/PCL	-	-	-	-	-	-
	PP (B)+	-	-	-	-	-	-
	PP/Starch	-	-	-	-	-	-
	Novel Starch 1	***	****	****	****	****	****
	Coconut	*	*	**	**	***	***
	PP(A)	-	-	-	-	-	-
	PP(B)	-	-	-	-	-	-
	Recycled Paper	***	****	****	****	****	****
	Starch Laminate	***	****	****	****	****	****
	Plantic	***	****	****	****	****	****
	Novel Starch 2	***	****	****	****	****	****
	Novel Starch 3	***	****	****	****	****	****
	Novel Starch 4	***	****	****	****	****	****
Microbial	Starch	**	***	***	****	****	****
	Paper	*	*	**	**	**	**
	PLA	-	-	-	-	-	-
	Silvergrass	*	*	**	***	****	****
	Starch/PCL	-	-	-	-	-	*
	PP (B)+	-	-	-	-	-	-
	PP/Starch	-	-	-	-	-	-
	Novel Starch 1	**	***	****	****	****	****
	Coconut	*	*	**	**	**	***
	PP(A)	-	-	-	-	-	-
	PP(B)	-	-	-	-	-	-
	Recycled Paper	-	-	-	-	*	**
	Starch Laminate	-	*	**	**	***	***
	Plantic	**	***	****	****	****	****
	Novel Starch 2	**	***	****	****	****	****
	Novel Starch 3	**	***	****	****	****	****
	Novel Starch 4	**	***	****	****	****	****

Property	Material	3	6	10	12	18	26
Fragmentation	Starch	*	**	***	***	***	***
	Paper	-	*	*	*	**	**
	PLA	-	-	-	-	-	*
	Silvergrass	-	*	*	**	**	***
	Starch/PCL	-	-	-	-	-	*
	PP (B)+	-	-	-	-	-	-
	PP/Starch	-	-	-	-	-	*
	Novel Starch 1	**	***	****	****	****	****
	Coconut	-	*	*	*	**	**
	PP(A)	-	-	-	-	-	-
	PP(B)	-	-	-	-	-	-
	Recycled Paper	-	-	-	-	-	*
	Starch Laminate	-	*	*	**	**	***
	Plantic	**	***	****	****	****	****
	Novel Starch 2	**	***	****	****	****	****
	Novel Starch 3	**	***	****	****	****	****
	Novel Starch 4	**	***	****	****	****	****
Integration	Starch	*	**	***	***	***	***
	Paper	-	-	-	-	*	**
	PLA	-	-	-	-	-	-
	Silvergrass	-	-	-	*	**	***
	Starch/PCL	-	-	-	-	-	-
	PP (B)+	-	-	-	-	-	-
	PP/Starch	-	-	-	-	-	-
	Novel Starch 1	**	***	****	****	****	****
	Coconut	-	-	-	-	*	**
	PP(A)	-	-	-	-	-	-
	PP(B)	-	-	-	-	-	-
	Recycled Paper	-	-	-	-	-	*
	Starch Laminate	-	*	*	**	***	***
	Plantic	**	***	****	****	****	****
	Novel Starch 2	**	***	****	****	****	****
	Novel Starch 3	**	***	****	****	****	****
	Novel Starch 4	**	***	****	****	****	****

Table 8.8: Alternative Table for Laboratory Experiment Two

Property	Material	10	20	32	39	50	60
Moisture	**Starch**	✱✱✱	✱✱✱✱	✱✱✱✱	✱✱✱✱	✱✱✱✱	✱✱✱✱
	Paper	✱✱	✱✱✱	✱✱✱	✱✱✱✱	✱✱✱✱	✱✱✱✱
	PLA	-	-	-	-	-	-
	Silvergrass	✱✱	✱✱✱	✱✱✱✱	✱✱✱✱	✱✱✱✱	✱✱✱✱
	Starch/PCL	-	-	-	✱	✱	✱✱
	PP (B)+	-	-	-	-	-	-
	PP/Starch	-	-	-	-	-	✱
	Novel Starch 1	✱✱✱✱	✱✱✱✱	✱✱✱✱	✱✱✱✱	✱✱✱✱	✱✱✱✱
Microbial	**Starch**	✱✱	✱✱✱	✱✱✱	✱✱✱✱	✱✱✱✱	✱✱✱✱
	Paper	✱	✱	✱✱	✱✱	✱✱	✱✱
	PLA	-	-	-	-	-	-
	Silvergrass	✱	✱	✱✱	✱✱✱	✱✱✱✱	✱✱✱✱
	Starch/PCL	-	-	-	✱	✱	✱✱
	PP (B)+	-	-	-	-	-	-
	PP/Starch	-	-	-	-	-	-
	Novel Starch 1	✱✱✱✱	✱✱✱✱	✱✱✱✱	✱✱✱✱	✱✱✱✱	✱✱✱✱
Fragmentation	**Starch**	✱	✱✱	✱✱✱	✱✱✱	✱✱✱	✱✱✱
	Paper	-	✱	✱	✱	✱✱	✱✱
	PLA	-	-	-	-	-	✱
	Silvergrass	-	✱	✱	✱✱	✱✱	✱✱✱
	Starch/PCL	-	-	-	-	-	✱
	PP (B)+	-	-	-	-	-	-
	PP/Starch	-	-	-	-	-	✱
	Novel Starch 1	✱✱✱✱	✱✱✱✱	✱✱✱✱	✱✱✱✱	✱✱✱✱	✱✱✱✱
Integration	**Starch**	✱	✱✱	✱✱✱	✱✱✱	✱✱✱	✱✱✱
	Paper	-	-	-	-	✱	✱✱
	PLA	-	-	-	-	-	-
	Silvergrass	-	-	-	✱	✱✱	✱✱✱
	Starch/PCL	-	-	-	-	-	-
	PP (B)+	-	-	-	-	-	-
	PP/Starch	-	-	-	-	-	✱
	Novel Starch 1	✱✱✱✱	✱✱✱✱	✱✱✱✱	✱✱✱✱	✱✱✱✱	✱✱✱✱

Key:
- = property unsuitable for degradation into compost
✱ = property just appropriate for a low level of degradation into compost
✱✱ = property at a good level for degradation into compost
✱✱✱ = property at a very high level for degradation into compost – supportive of a maximum degradation rate
✱✱✱✱= could not be assessed as conversion into compost was complete

In general, the breakdown of the laboratory specimens was visually very similar to that of the small specimens and whole units, confirming the validity of the experiment. The second laboratory experiment predicts what would happen if the whole units were composted over 6 months in a domestic composter.

8.6.3.2 Mass Loss and Moisture Content of the Laboratory Scale Experiments

The results of mass loss (extent of biodegradation) for the first and second laboratory experiment are given in figures 8.19 and 8.20 respectively.

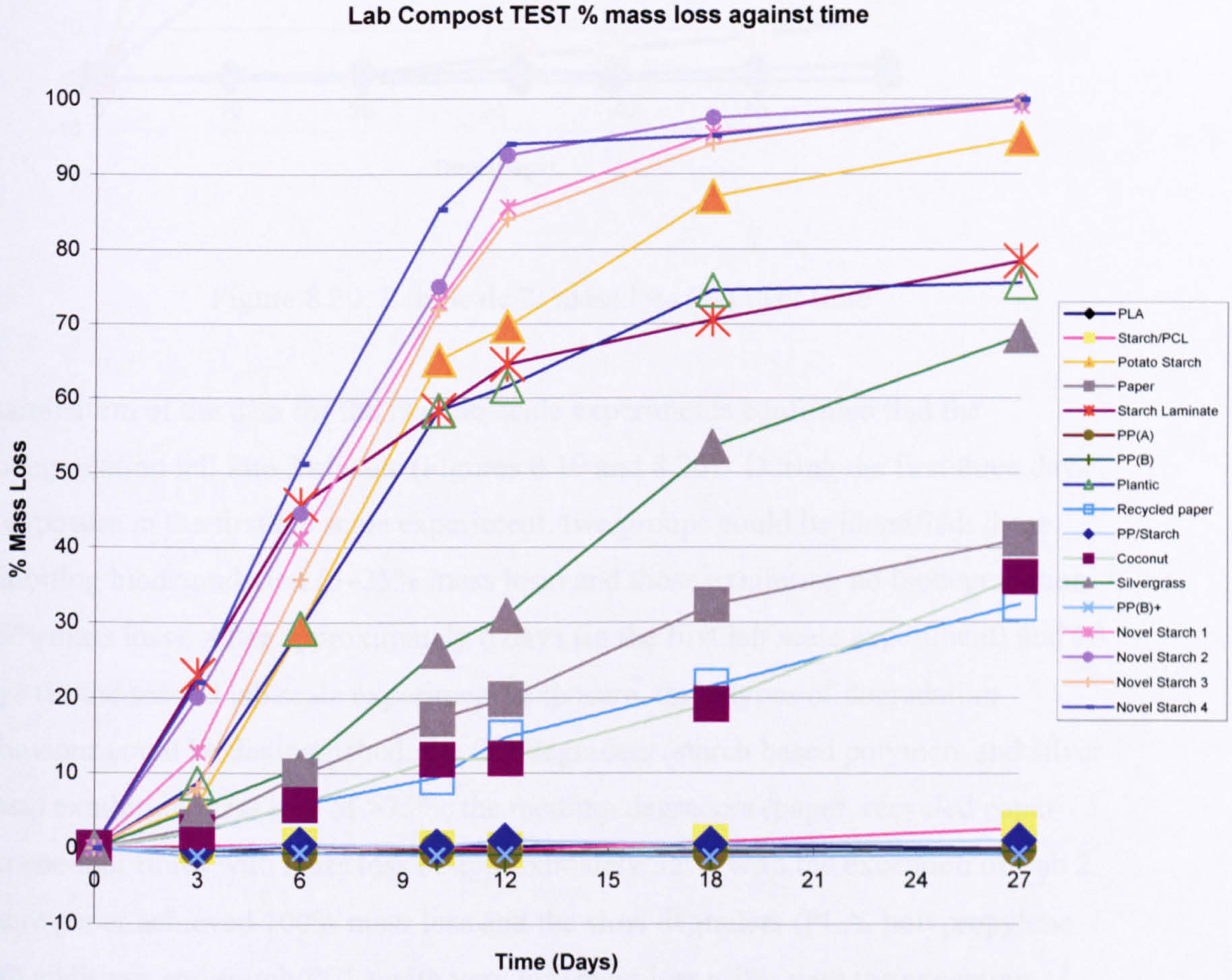


Figure 8.19: Lab Scale 1 mass loss (%) against time

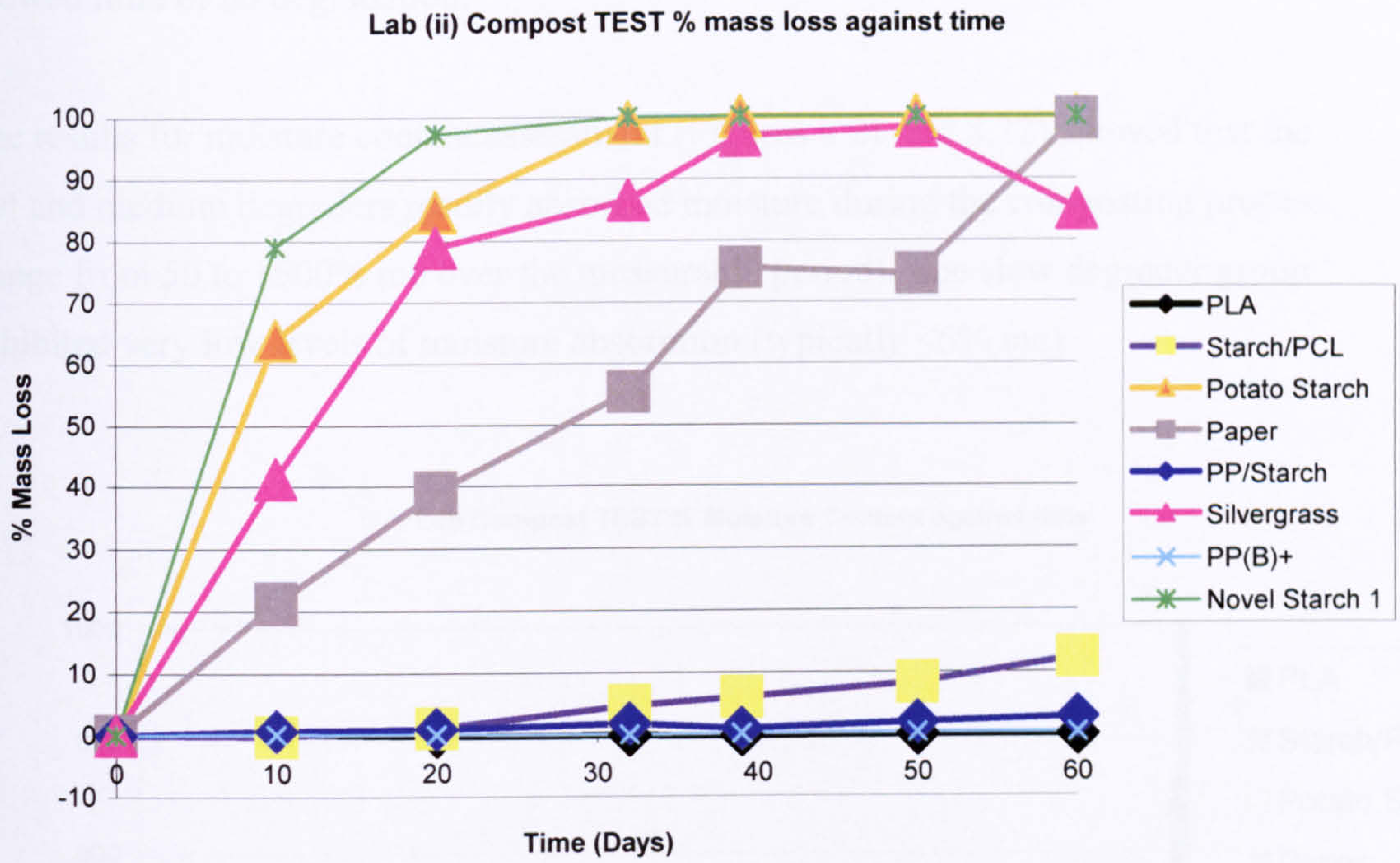


Figure 8.20: Lab Scale 2: mass loss (%) over time

Examination of the data for the two lab-scale experiments confirmed that the biodegradation fell into 3 classes (Figures 8.19 and 8.20). During the first three days of exposure in the first lab scale experiment, two groups could be identified: those exhibiting biodegradation (5–25% mass loss) and those exhibiting no biodegradation (<5% mass loss). After approximately 6 days (in the first lab scale experiment) and 10 days (in the second lab scale experiment) exposure, three types of degradation behaviour could be distinguished: the fast degraders (starch based polymers and silver grass) exhibiting mass loss of >75%, the medium degraders (paper, recycled paper and coconut fibre) with mass loss of approximately 35%, with the exception of Lab 2 where paper achieved 100% mass loss and the slow degraders (PLA, polypropylene with additives and starch/PCL) with very low mass loss <5%, with the exception of starch/PCL in lab two which achieved over 10% mass loss. This differentiation of 3 clear groups then continued to the conclusion of the both experiments at 27 and 60 days respectively, with readily degradable materials becoming indistinguishable from their sealed packets. The middle group showed extensive degradation but remained recognisable on close inspection, with the exception of paper in the second lab experiment. The slow degrading materials were clearly recognisable as such and showed little or no degradation.

The results for moisture content assessment (Figures 8.21 and 8.22) showed that the fast and medium degraders readily absorbed moisture during the composting process (range from 50 to 1500% mc over the measurable period). The slow degrader group exhibited very low levels of moisture absorption (typically <5% mc).

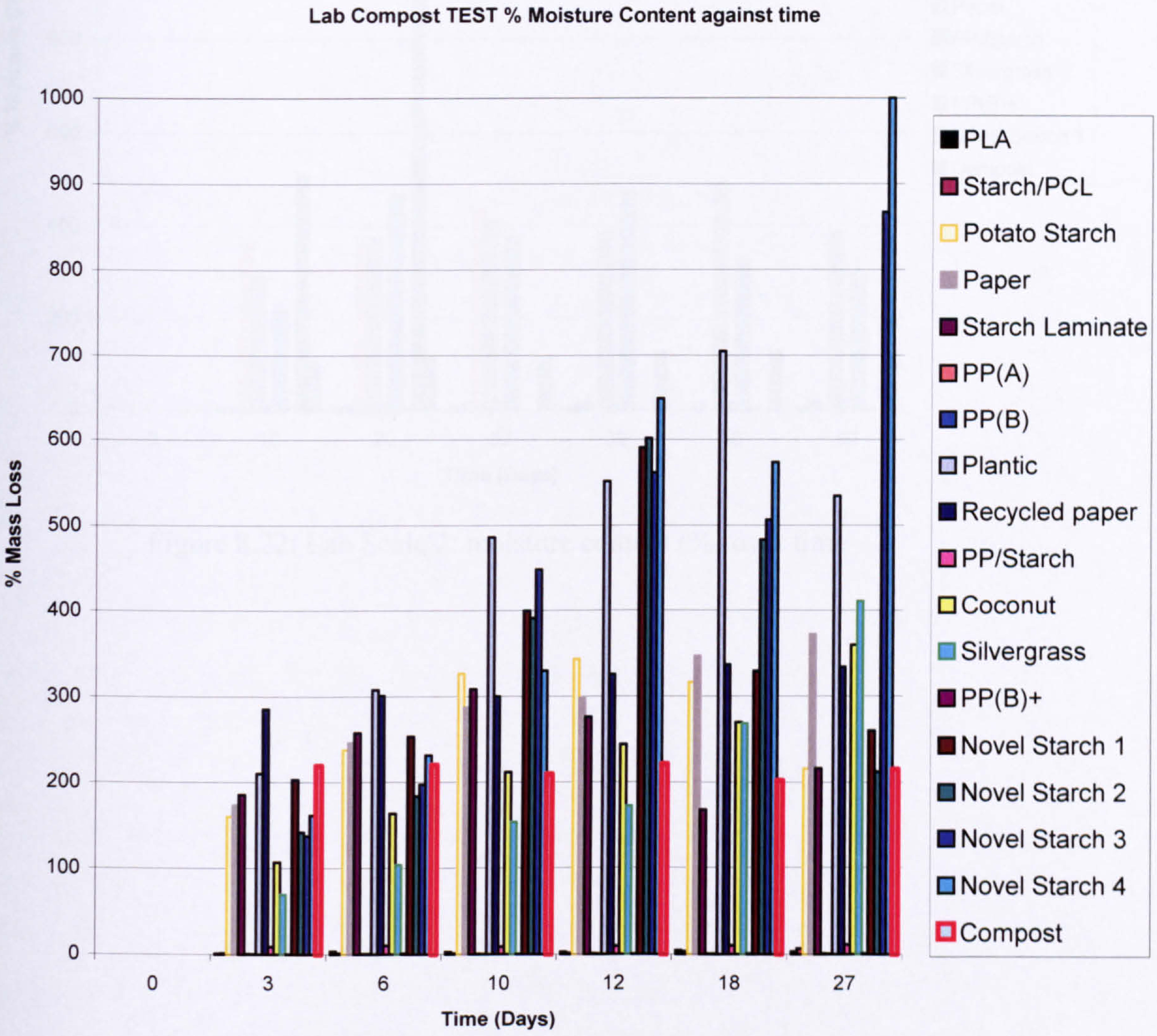


Figure 8.21: Lab Scale 1: moisture content (%) over time

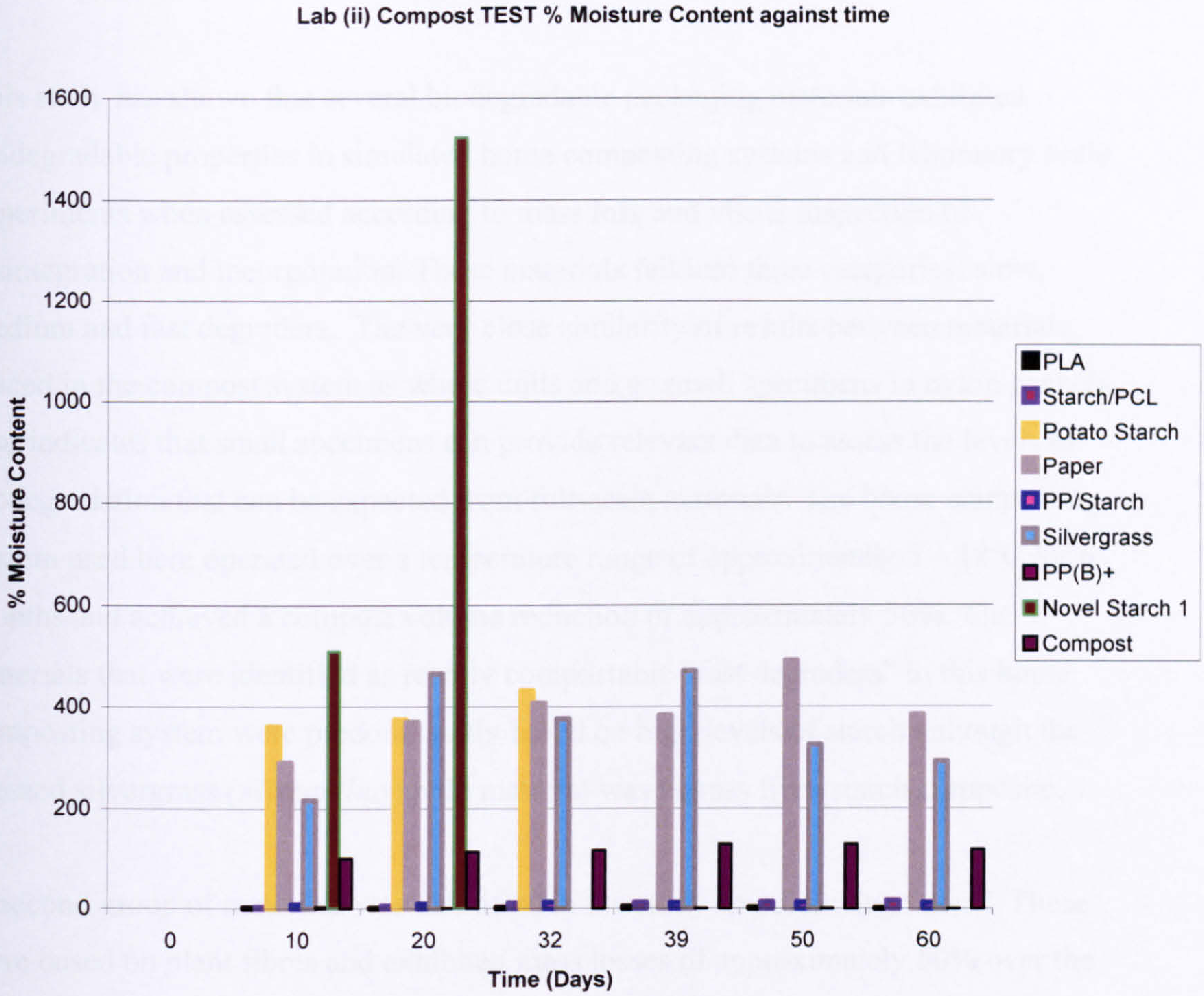


Figure 8.22: Lab Scale 2: moisture content (%) over time

8.7 Discussion and Conclusions

This study has shown that several biodegradable packaging materials exhibited biodegradable properties in simulated home composting systems and laboratory scale experiments when assessed according to mass loss and visual inspection of disintegration and incorporation. These materials fall into three categories: slow, medium and fast degraders. The very close similarity of results between materials placed in the compost system as whole units and as small specimens in nylon packets also indicates that small specimens can provide relevant data to assess the levels of biodegradation that can be expected from full-scale materials. The home composting system used here operated over a temperature range of approximately 5 – 18°C for 6 months and achieved a compost volume reduction of approximately 50%. The materials that were identified as readily compostable "fast degraders" in this home composting system were predominantly based on high levels of starch although the pressed silvergrass (*Miscanthus*) pulp material was a grass fibre/starch composite.

A second group of materials was identified in the study "medium degraders". These were based on plant fibres and exhibited mass losses of approximately 50% over the six month low temperature composting period. The extent of degradation in these materials over this period and the easily fragmentable nature of the residual material the end of the period indicates that these would be acceptable for home composting. They are readily incorporated into the compost matrix after approximately 4 to 6 months of low temperature composting.

The third group of materials identified: the "slow degraders", exhibited no or very low levels of biodegradation or fragmentation over the composting period. It is known that elevated temperature, for example 60°C, can be an important parameter enabling the induction of biodegradation of polymers such as PLA [2 & 3 & 4]. Such temperatures are clearly lacking in the home composting system and even prolonged exposure over 6 months did not lead to evidence of biodegradation. An exception to this was the starch/PCL material study in which mass loss began to be induced after 5 and 6 months of exposure (3 and 6% mass loss respectively) and this was associated with increased absorption of moisture at this time. In all cases of slow/no biodegradation the materials showed very low or zero moisture absorption during the earlier part or the whole of the composting period and this is clearly a factor limiting the induction of biodegradation.

It is interesting that three 'groups' of biodegradability behaviour in home composting were clearly recognisable from the data for both whole unit materials and small specimens. This has been interpreted as indicating that the materials types studied do segregate into a limited number of well defined categories and that this is associated with fundamental properties of these materials that affect their performance in low temperature biodegradation and composting. It appears most likely that readily biodegradable types such as the high starch materials (but also silvergrass/starch material) quickly absorb moisture and become amenable to microbial digestion which proceeds rapidly. Less easily attacked materials like cellulose paper and lignified plant fibres (e.g. coconut) also absorb moisture well but their degradation rate is limited by the accessibility of their polymeric structures to microbial digestion, which consequently proceeds at a slower rate. Finally, the low or non-degradable materials in this low temperature composting environment such as PLA are resistant to moisture absorption and have a molecular structure that does not enable microbial degradation. It is probable that some materials in this latter category may become susceptible to microbial attack after prolonged exposure (for example: starch/PCL composite) and that once started, microbial degradation is likely to proceed at a slow rate, assuming conditions remain favourable.

The seed germination study using the methodology of PAS 100 has shown that composts made from green waste incorporating approximately 6% by mass of home composted starch or paper trays gives growth media that support good seed germination and seedling development. Similar results were achieved with compost incorporating non-biodegraded PLA materials, although seedling fresh mass was somewhat reduced compared with controls. Similar reductions in seedling mass in composts with degradable polyethylene and control composts from open windrow systems have been found by Davis *et al* [5].

Both laboratory-scale experiments one and two validated the home composting results and provide an opportunity to test materials in controlled conditions over a short time period. The ability to use less sample materials and accurately predict the outcome of what would occur should the sample material be tested in a full-scale home composter has many commercial benefits.

It is apparent from this study that several biodegradable packaging materials can be processed in home composting systems and yield compost materials suitable for plant growth. This capability will enable such materials to be disposed of in well-run home composting systems and result in waste diversion from municipal waste streams. However, the study has also demonstrated that a number of packaging materials that will typically biodegrade well in industrial, high-temperature composting systems failed to biodegrade in the low temperature home composting environment (for example: PLA and starch/PCL blend <5% weight loss in home composting).

At a practical level, and to avoid confusion for consumers, these results suggest that it is very important to clearly distinguish those biodegradable packaging materials that can be expected to perform well in home composting systems from those where biodegradation can only be expected in industrial composting systems. Labelling schemes and consumer information should support such a distinction and the RE would recommend that the 'default' setting for a material to be defined as biodegradable and compostable should apply to materials that can show such behaviour in both home ***and*** industrial composting. Those that will only biodegrade in industrial composting systems (e.g. as shown by compliance with EN 13432)[6] should be defined as 'industrially compostable'. The standard EN 13432 should also include a chapter on 'home composting'.

The information presented in Chapter eight was used in Chapter seven LCA waste scenarios.

In conclusion not all the 'biodegradable materials' tested are suitable for 'home composting'.

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CHAPTER 9: OVERALL RESULTS AND CONCLUSIONS

9.0 Overall Results and Conclusions

This chapter draws conclusions from the previous work carried out, reflects on the contributions to knowledge made during this research project and provides recommendations for further research.

The food packaging industry is a huge global industry growing at a rate of 12% per year and generates 58m tonnes of plastic packaging waste in the EU. This project highlights short-term solutions to reduce industrial waste and contributes towards a longer-term sustainable solution by providing a baseline formulation for a biodegradable material that is home compostable. The following paragraphs recap the aims of the research project and specify how each of the individual projects carried contributed towards achieving the objectives.

9.1 Project Aims

1. To reduce waste by improving material utilisation within current processes and working practices using existing technology and oil-based materials.

2. To assess the suitability and economic viability of new-generation "biodegradable"/"sustainable" materials in the market for food packaging applications.

3. To develop an alternative material with suitable properties that can be made from a low cost, renewable resource such as starch.

4. To carry out a Life Cycle Assessment (LCA) to evaluate the environmental profile of biopolymers versus oil-based polymers through the supply chain, production, use and final waste disposal options. To conclude which of these two material types is more environmentally sustainable for the packaging industry and to identify which disposal route is best for each polymer.

5. To determine the extent of biodegradation that may occur when bio-based or biodegradable packaging materials are disposed of under a simulated domestic

(home) composting regime and establish which of a range of potentially biodegradable packaging materials would show levels of biodegradation appropriate for disposal at their end-of-life via home composting together with green garden waste.

9.2 Results and Conclusions

9.2.1 Reducing the Environmental Impact of Pactiv's Production

The changes implemented as a result of the work carried out by the Research Engineer were a resounding success and provided Pactiv Europe with short-term solutions to improve on its environmental footprint, whilst entailing the significant cost savings required to ensure its continued competitiveness and market positioning. Simply by changing working practices and increasing staff awareness of the importance of focussing on recycling and correctly segregating waste materials for re-work or re-processing, significant improvements were achieved.

By increasing the proportion of rework used, the amount of virgin material required and the volume of waste plastic was substantially reduced. This was achieved by improving material identification, improving the segregation of waste materials, improving storage facilities and practices and by employing more recycling equipment and operators. Furthermore, new revenue streams were found by reprocessing materials that did not meet food hygiene standards and selling them for lower grade applications rather than sending them to landfill. In short, by implementing measures to tackle the environmental impact of its production process, Pactiv also achieved a direct positive impact to its cost structure and working practices. If similar studies were applied to other organisations in the industry, a larger scale reduction in environmental impact could be achieved in the short-term. In the longer term, consideration of environmental impact will focus on the types of material used.

9.2.2 Potential Biodegradable Alternatives to Conventional Polymers

Of all the materials studied, PLA is the only commercially available material that has suitable physical and mechanical properties. In the current market PLA is the only viable alternative to current oil-based polymers for the food packaging industry. By analysing the processing of these materials from granule form to extruded sheet using Pactiv's existing production facilities, the Research Engineer established the foundations and the first step towards the ultimate goal of adopting a sustainable, biodegradable, thermoformable and affordable material for the production of food packaging trays.

9.2.3 Development of a Novel Starch-based Material

All samples tested to date have successfully formed an extrudate using combinations of purified wheat starch and glycerol that can be vacuum-formed into a **colourless** packaging tray.

The mechanical properties of the purified wheat starch and glycerol are lower than for conventional oil-based plastics such as polypropylene (figure 6.19).

Observations of the material kept from the first trials suggest that the mechanical properties, in particular impact strength, reduce with time. Therefore all the "A" blends have been re-trialed and mechanically tested with respect to time.

The preliminary study was a success and proved that it is possible to produce a low-cost biodegradable sheet material that can be formed into a packaging tray. A baseline formulation was established for the full scale DEFRA Foodlink project.

9.2.4 The Comparative LCA of Biopolymers and Oil-based Polymers suitable for Food Packaging

The LCA supports the studies carried out by environmental pressure groups such as 'Green Peace' and agrees with their Pyramid of Poisonous Plastics, which ranks PVC as the most damaging in environmental terms.

The government and pressure groups have been strongly supporting the need for biopolymers and this LCA further confirms the need for biopolymers such as Novel Starch, which degrades in a low composting systems.

The LCA concludes that biopolymers such as PLA are an improvement in terms of limiting environmental damage. The main difference between Novel starch and PLA is the energy consumed during their production / PLA requires more processing stages to manufacture. The PLA data set used shows that higher levels of transportation are required for PLA than for Novel starch because the PLA used is manufactured in the US.

The research highlighted in chapter five suggests that Cargill Dow's anticipated future manufacturing processes will incur a considerable reduction in the fossil fuel required to manufacture PLA. Given this, we can expect to see the profile of PLA reduce in terms of environmental damage, although it currently scores highly in terms of fossil fuel usage.

To date, Novel starch has only been manufactured on a laboratory scale and as such some process improvements and economies of scale can be expected if it were manufactured on an industrial scale. However, not all properties of Novel starch have been evaluated for commercial use (it is a development product). More additives would be needed for its commercial success.

The use of two impact assessment methods has enabled a more balanced conclusion regarding the LCA of biopolymers compared to oil-based polymers.

In conclusion biodegradable polymers are an environmental improvement over current oil-based polymers.

Home composting is the most desirable waste management option for food packaging waste most currently available biopolymers are only suitable for high temperature composting systems.

9.2.5 Home Composting of Biodegradable Polymer Packaging Materials

This study has shown that several biodegradable packaging materials exhibited biodegradable properties in simulated home composting systems and laboratory scale experiments when assessed according to mass loss and visual inspection of disintegration and incorporation. These materials fall into three categories: slow, medium and fast degraders. The very close similarity of results between materials placed in the compost system as whole units and as small specimens in nylon packets also indicates that small specimens can provide relevant data to assess the levels of biodegradation that can be expected from full-scale materials. The home composting system used here operated over a temperature range of approximately 5 – 18°C for 6 months and achieved a compost volume reduction of approximately 50%. The materials that were identified as readily compostable "fast degraders" in this home composting system were predominantly based on high levels of starch although the pressed silvergrass (*Miscanthus*) pulp material was a grass fibre/starch composite.

A second group of materials was identified in the study: "medium degraders". These were based on plant fibres and exhibited mass losses of approximately 50% over the six month low temperature composting period. The extent of degradation in these materials over this period and the easily fragmentable nature of the residual material the end of the period indicate that these would be acceptable for home composting. They are readily incorporated into the compost matrix after approximately 4 to 6 months of low temperature composting.

The third group of materials identified, the "slow degraders", exhibited no or very low levels of biodegradation or fragmentation over the composting period. It is known that elevated temperature, for example 60°C, can be an important parameter enabling the induction of biodegradation of polymers such as PLA [1 & 2 & 3]. Such temperatures are clearly lacking in the home composting system and even prolonged exposure over 6 months did not lead to evidence of biodegradation. An exception to this was the starch/PCL material study in which mass loss began to be induced after 5 and 6 months of exposure (3 and 6% mass loss respectively) and this was associated with increased absorption of moisture at this time. In all cases of slow/no biodegradation the materials showed very low or zero moisture absorption during the earlier part or the whole of the composting period and this is clearly a factor limiting the induction of biodegradation.

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Both laboratory-scale experiments one and two validated the home composting results and provide an opportunity to test materials in controlled conditions over a short time period. The ability to use less sample materials and accurately predict the outcome of what would occur should the sample material be tested in a full-scale home composter has many commercial benefits.

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At a practical level, and to avoid confusion for consumers, these results suggest that it is very important to clearly distinguish those biodegradable packaging materials that can be expected to perform well in home composting systems from those where biodegradation can only be expected in industrial composting systems. Labelling schemes and consumer information should support such a distinction and the RE would recommend that the 'default' setting for a material to be defined as biodegradable and compostable should apply to materials that can show such behaviour in both home ***and*** industrial composting. Those that will only biodegrade in industrial composting systems (e.g. as shown by compliance with EN 13432)[5] should be defined as 'industrially compostable'. The standard EN 13432 should also include a chapter on 'home composting'.

The information presented in Chapter eight was used in Chapter seven LCA waste scenarios.

In conclusion not all the 'biodegradable materials' tested are suitable for 'home composting'.

9.3 Recommendations for further work

Chapter 8: Following my recommendation of carrying out a simulated in-vessel / open windrow composting for PLA to prove that it does break down in a high temperature composting system. Dr Richard Murphy and one of his undergraduate students at Imperial College carried this out and concluded that PLA does indeed breakdown in a high temperature composting system.
Following from this investigation further research is needed to determine whether the temperature or the microbes at the higher temperature or a combination of both is necessary to break down the polymer.

Chapter 5: The mechanical and biodegradable properties of the samples are to be tested.
Research will continue to keep up to date with materials such as Wells Plastics and Add –X, biodegradable additives and other new materials that become commercially available, with a view to making Pactiv's current grades of oil-based plastics more biodegradable.

Chapter 6: Issues to be investigated further include the mechanical properties of the purified wheat starch and glycerol which are lower than for conventional oil based plastics such as Polypropylene.
The highest impact strength of the notched samples, for example, is 5.52 KJ/m^2 which is very low compared to the average impact strength of Neste Chemicals N.V grade of polypropylene which is 15.52 KJ/m^2.

Observations of the material kept from the first trials suggest that the mechanical properties, in particular impact strength, reduce with time. Therefore all the A blends have been re-trialed and mechanically tested with respect to time.

Further work will include additional mechanical and physical testing and composting tests.

The issue of bacterial growth also needs to be investigated. It is thought that the bacterial growth is directly related to the water content of the blends when stored.

Further trials will use the purified wheat starch rather than the wheat flour. This raises the issue of the cost of the purified wheat starch compared to the wheat flour, which needs to be taken into consideration if this is to be a low cost solution.

9.4 Contribution to Knowledge

The particular aspects of the work that are original contributions to knowledge include:

- Processing a low cost thermoplastic starch material suitable for the extrusion and vac forming of a packaging tray on a laboratory scale.
- Whereas previous work has investigated industrial composting, no data existed for domestic composting. This project showed that the majority of the materials deemed "biodegradable" do not in fact decompose under low-temperature home composting conditions. Furthermore, this project revealed that biodegradable materials fall into 3 categories: Fast, medium and slow degraders.
- A laboratory-scale version of the domestic composting trial was devised. This showed that lab-scale results correlate to domestic-scale results. As such, the biodegradability of materials can be assessed on a lab-scale and the results used to predict the results of domestic composting. This is not only more efficient -on a lab-scale there is less specimen material requirement and conditions can be controlled - but enables the method to be used commercially to enable faster assessment of new materials.
- The plethora of polymer materials with vastly differing properties on the market makes disposal choices confusing and difficult, especially for consumers. The LCA highlights which end of life scenario is most suitable for each of the polymers tested.

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APPENDIX A: 2003 CONFERENCE PAPER FOR THE ENGINEERING DOCTORATE IN ENVIRONMENTAL TECHNOLOGY

ENVIRONMENTAL PACKAGING

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Abstract

Over 67 million tonnes of packaging waste is generated annually in the EU, which constitutes one third of all municipal solid waste. Approximately 22 million tonnes of packaging waste has an oil based feedstock, which on the whole is not biodegradable and becomes difficult to recycle or reuse when mixed with other material types. Plastic food packaging is often seen in the form of litter in our lives and as such has caused increasing environmental concern.

This paper discusses the Engineering Doctorate project between Brunel University and Pactiv Europe, a food-packaging manufacturer. The project uses two approaches to improve the sustainability of the packaging industry. Reduce materials going to landfill and the development of biodegradable packaging materials.

Pactiv (UK) uses approximately 30,404 tonnes of oil based polymer to manufacture plastic food packaging. Detailed analysis of Pactiv's waste stream has highlighted major material losses during manufacture of the plastic packaging. Approximately 3797 tonnes of plastics ends up either in landfill or in a low grade, non food packaging applications. This project aims to reduce the tonnage of waste going to landfill by improving on Pactiv's internal recycling and finding/developing markets for the materials that can not be internally recycled.

Development of biodegradable or compostable food packaging has been highlighted as one solution to the solid waste problem. The Environmental Packaging project aims to evaluate the commercially available materials, which exhibit environmental characteristics such as: compostability, sustainability. Initial analysis has shown Polylatic Acid (PLA), Cargill Dow and Materbi, Novermont, are potential candidates from a performance and compostability point of view. However high prices are barriers to commercial implementation. Starch based technologies are being investigated to produce a low cost, compostable, thermoformed, food packaging tray with good clarity and appropriate mechanical/barrier properties.

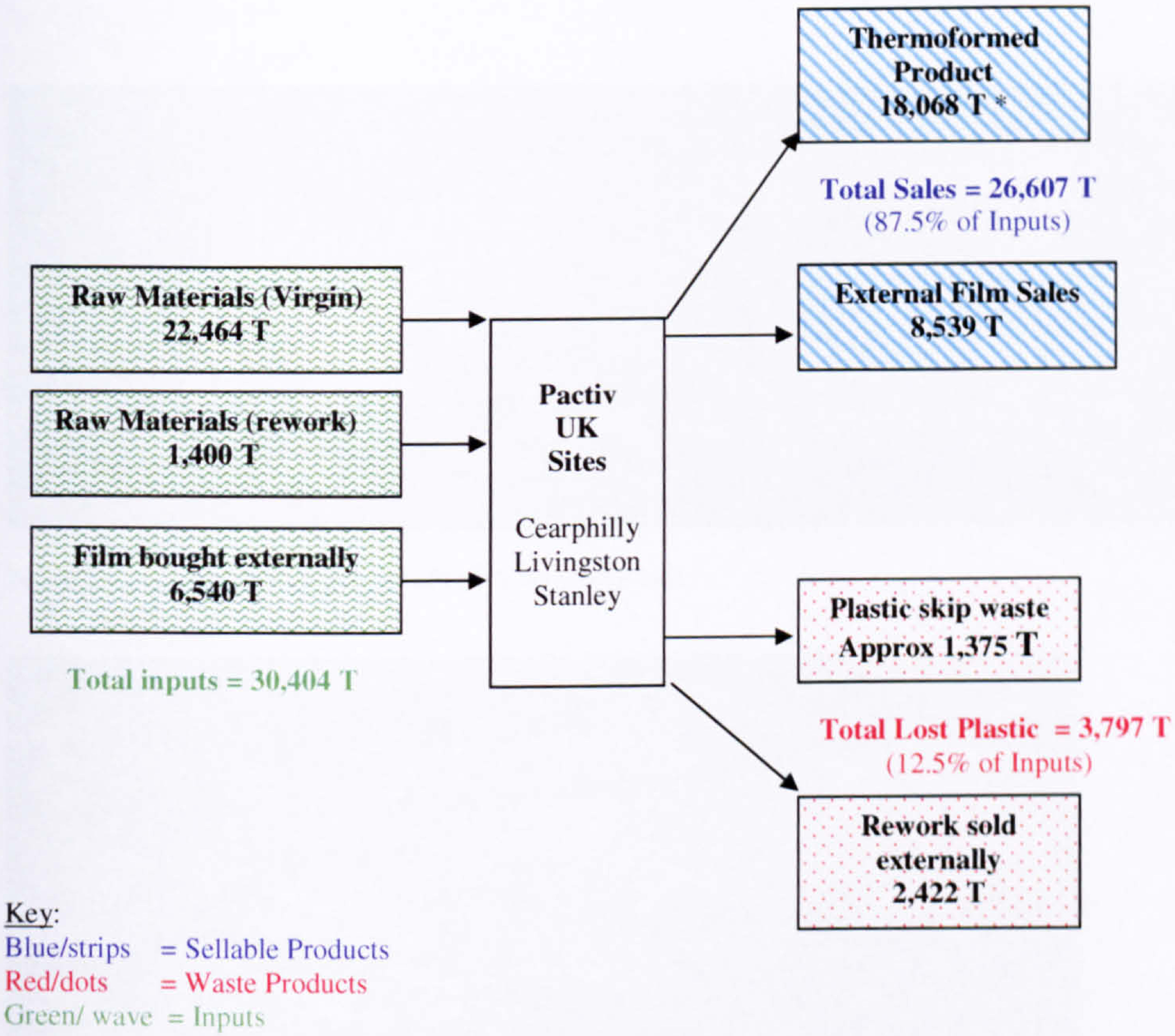
Keywords: Environmental, Biodegradable, Compostable, Starch, Packaging, Polylatic Acid, (PLA), Materbi, Compostable Additives, Recycling, Landfill Sustainable.

1.0 Industrial Waste Minimisation Project

A typical definition of packaging is "packaging must protect what it sells and sell what it protects."[1] Other important features of packaging include minimal cost, maximum convenience and recyclability.

Packaging can thus be evaluated by the following criteria: Appearance, Protection, Function, Cost and Disposability.

Pactiv UK is a typical food packaging company and as such the problems it experiences with recycling are typical issues of the industry as a whole.



* Thermoformed Product Total weight calculated from Total inputs – (Total Lost Plastic + External Film Sales)

Figure 1 Basic Inputs & Outputs of Pactiv UK's three Thermoforming / Extrusion sites [2].

Analysis of Pactiv's basic inputs and outputs shows that 3,797 tonnes, as shown in Figure 1.0, of plastic material is lost from the food packaging business, which is 13.1 % of total material inputs. It is estimated that 1375 tonnes of plastic is disposed via skips into landfill. Pactiv's waste contractor charges approximately £66 per tonne to dispose of this plastic, which equates to a cost of £ 90,750 to Pactiv all of which could be potentially recovered.

Sold rework refers to material that is sold to scrap dealers for a small proportion of its original purchase price, for example Pactiv pays £450 per tonne virgin material and sells it, to scrap dealers, for approximately £50 - £100 per tonne. The material sold is usually clean and suitable for food contact applications. However, often it is coloured and is therefore only suitable when thermoforming black products.

In practice there are limited black products that can be used as 'sinks' for this material. In 2002 2,422 tonnes, was sold off to rework dealers resulting in approximately £ 908,250 of lost material value, which equates to approximately 8 % of all raw materials inputs. This is an area, which has a major impact on material efficiency and costs of the business.

£181,500 is currently being spent in removing and disposing 2750 tonnes of waste, similar to that in Figure 2, from the three UK sites, all of which currently ends up in landfill similar to that in Figure 3.

Figure 2 An example of what goes into Pactiv's compactor bins

Figure 3 A Landfill site where the waste from Pactiv's compactor bins ends up.

Further investigation is needed to highlight the percentage of plastic, which could be usefully re-used. It is estimated that this could be up to 1375 tonnes. Selling this material to companies, who don't require food hygiene standards, would benefit the environment and generate some financial revenue, estimated to be between £50k and £100k per year. Further more, separating the skip waste currently going to landfill, will further promote reuse and reduce landfill costs.

2.0 Biodegradable Food Packaging Project

During the last decade, polymers obtained from renewable resources have attracted increasing attention, due mainly to their environmental image and potential for sustainability.

Trying to find solutions for environmental problems the World Commission on Environment and Development (1987) put forward the concept of sustainable development. "Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs."[3]

There are some problems with this concept. Namely we are very aware of the environmental problems of today but we are not informed in detail about the problems to come. Some future problems are easier to predict due to them having roots in the existing problems. There are however problems that do not or are not known to currently exist. This is the challenge that we as a human race have set ourselves to solve.

A definition of biodegradation given by the CEN (European Committee of Standardisation). "A biodegradable material is called biodegradable, with respect to specific environmental conditions. If it undergoes biodegradation to a specific extent within a given time measured by standard test methods and biodegradation is a degradation caused by biological activity especially by enzymic action leading to a significant change of the chemical structure of a material."[4]

Man has recognised the need to reduce the amount of municipal plastic waste being sent to landfill. Indeed the whole idea of landfill is being seriously questioned. Alternatives such as incineration, which current facilities are running at maximum capacity, are likewise criticised as highly energy intensive. Improved recycling methods of commodity plastic materials have helped to accomplish the goal of waste reduction. There are end use applications, however where product and materials recycling are neither practical nor economically feasible. Examples tend to include heavily contaminated light weight items, such as rubbish bags and disposable products i.e. food packaging. These are prime examples where materials, which would breakdown (biodegrade) under a wide variety of environmental conditions, including composting, would be beneficial. Generally plastics originate from non-renewable resources such as oil. The dependence of plastics on oil can be reduced initially by the use of biopolymers and eventually by technology which uses conversion energy as a source of power rather than oil. Biopolymers are polymers synthesised by nature or derived from natural and renewable materials. Research is currently being carried out into the commercial applicability of biotechnology to the development of new products involving the use and modification of natural substances such as starch, cellulose, silk and others.

Currently, few plastics are derived from natural products such as wood, starch and natural oils. Renewable raw materials are of industrial interest if their structure leads directly to polymers, or to easy to produce and convert intermediates and monomers. However, as a source of chemical base products, they have several disadvantages with respect to petroleum. Generally renewable raw materials are chemical compounds or mixtures of chemical compounds and hence quite complex in composition and properties. Their Carbon hydrogen ratio is less favourable for the manufacture of base chemicals. Their conversion into intermediates or monomers also requires more energy than that of petroleum.

Other disadvantages of renewable materials include the current price deferential between biodegradable polymers and traditional oil based polymers. Currently prices of biodegradable polymers, such as PLA and starch blends, are three times more than traditional polymers. It is hoped that this differential will reduce with economies of scale, technology improvements and competition.

There are many types of biodegradable materials such as those made from natural fibre and polymers formulated to biodegrade. Starch is however by far the major contender and most explored as an alternative to plastics.

2.1 Sustainable / Biodegradable Packaging Materials

Current commercially available sustainable/ biodegradable packaging materials have been investigated, with some degree of success. Taking us closer still to the ultimate goal of a sustainable, biodegradable thermoformable material which can be used to produce food packaging trays.

Materials investigated include: Polylatic Acid (PLA) trade name Natureworks™ from Cargill Dow, as shown in Figure 4; Materbi, SGC 2763 from Novermont, a starch based biopolymer, as shown in Figure 5 and an oil based polymer combined with a biodegradable additive, BD 92397, from Wells Plastics, as shown in Figure 6.

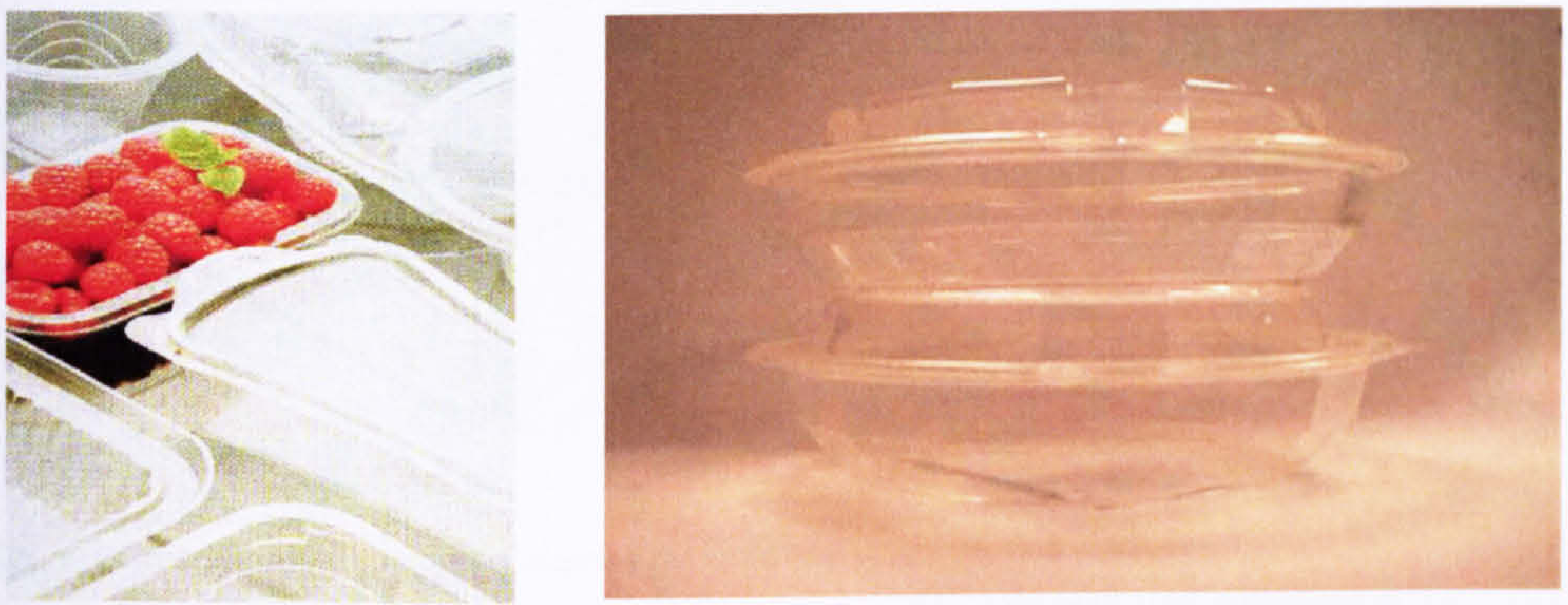


Figure 4 Polylatic Acid (PLA) Thermoformed Food Packaging Trays from Pactiv.

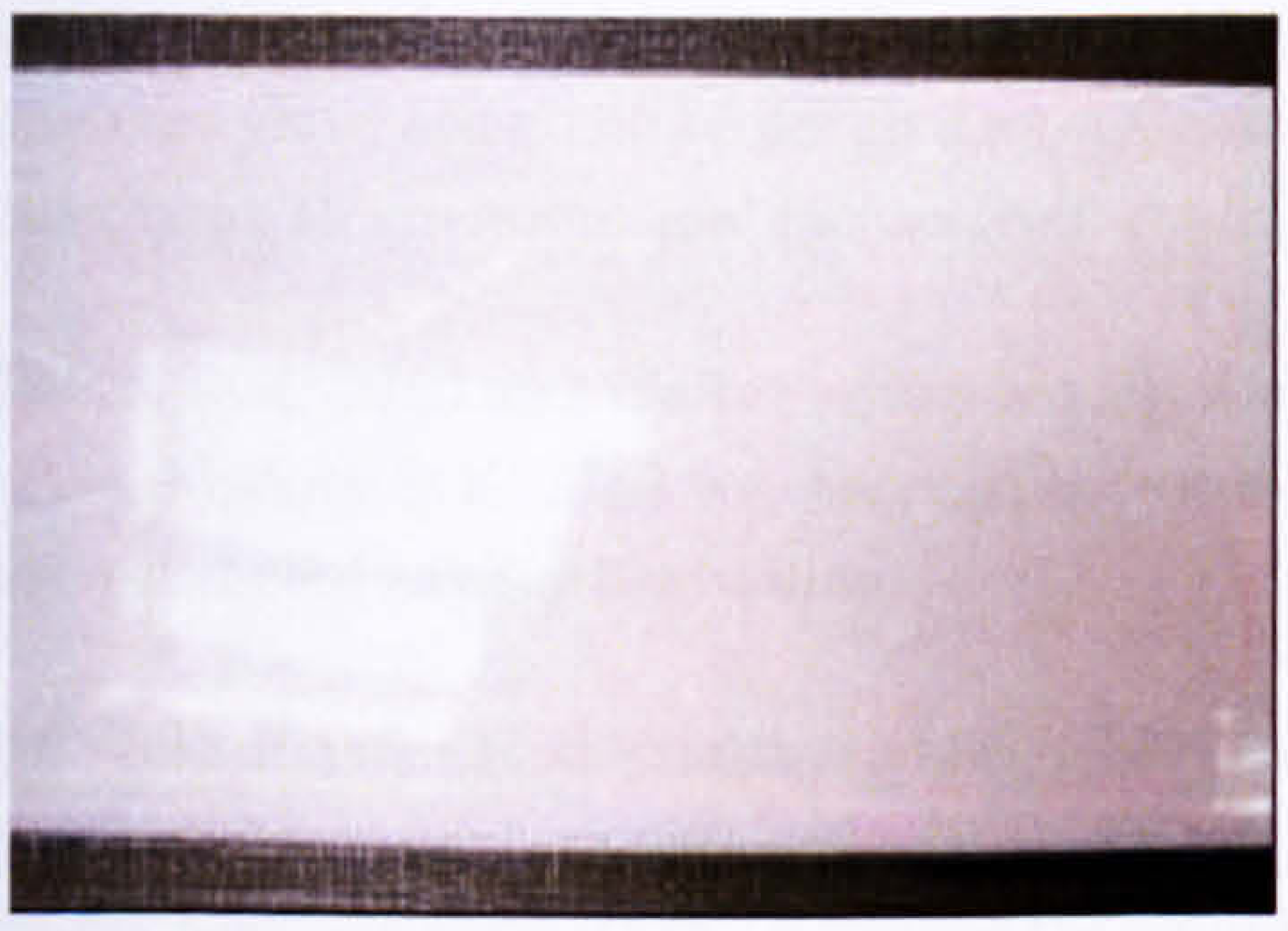


Figure 5 Materbi SGC 2763 from Novermont

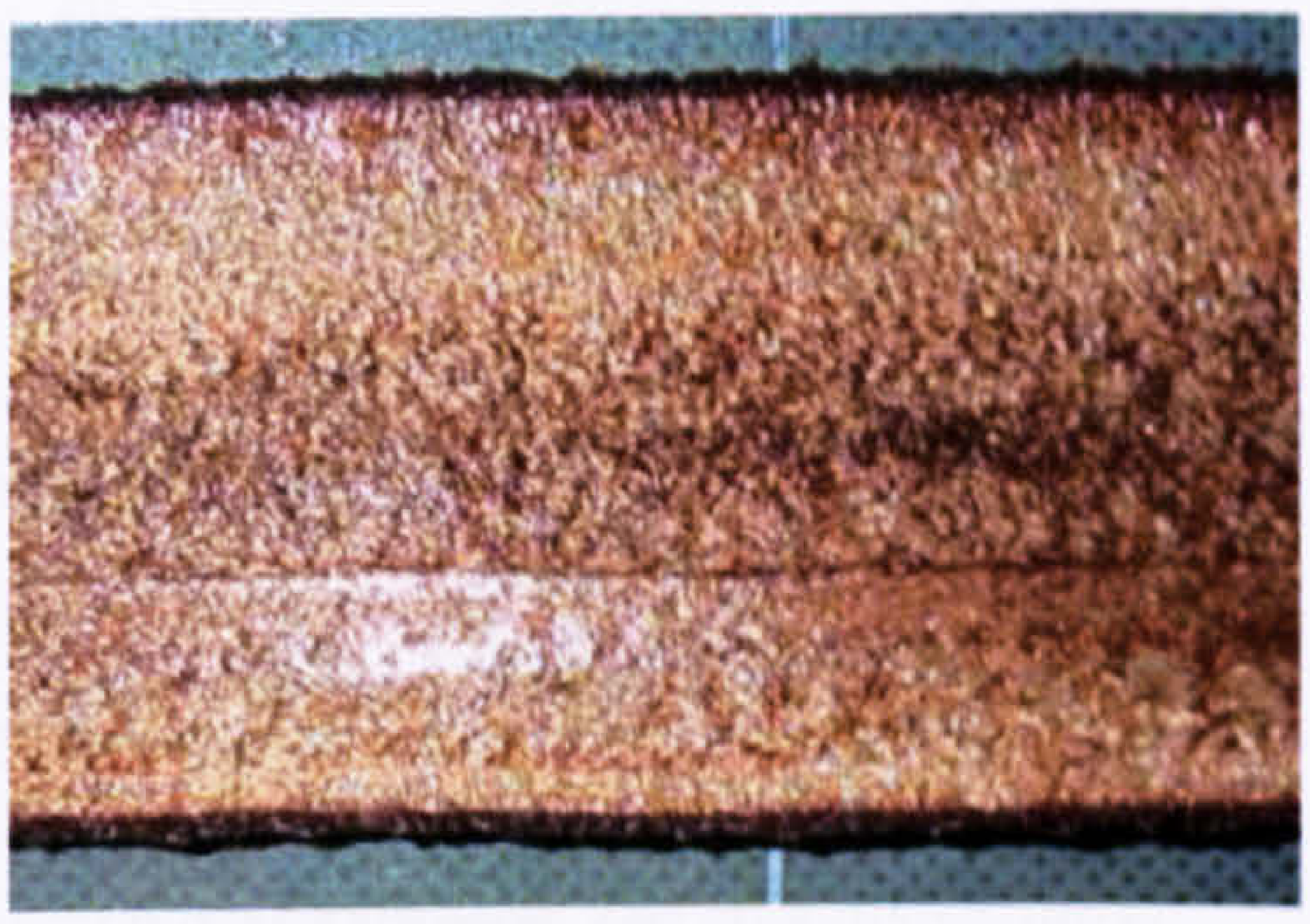


Figure 6 Oil based polymer combined with a Biodegradable Additive, BD92397 from Wells Plastic

PLA has been successfully thermoformed on an industrial basis. Pactiv now have a range of thermoformable 'natural' compostable packaging, including trays, hinged packs and confectionary selection packs, all of which can be seen in Figure 4.0. PLA is derived from sustainable carbon harvested from plants such as corn. The physical properties of PLA are similar to Amorphous terephthalate (APET) and Polystyrene (PS), which are both typical examples of current oil based plastics used in the food packaging industry. Impact resistance, rigidity and clarity are all comparable to PS, whilst the service temperature and density are closer to APET. The PLA samples are currently awaiting approval from one of Pactiv's leading customers, who has made the decision to eliminate all of the PVC packaging from its shelves. The approval may not be granted due to cost, as PLA is three times the price of APET, another non PVC alternative. APET is however a conventional oil based plastic, although it is ranked lower, number 3, on Green Peace's poisonous plastics pyramid, as shown in Figure 7, it is not from a sustainable source and is not compostable.

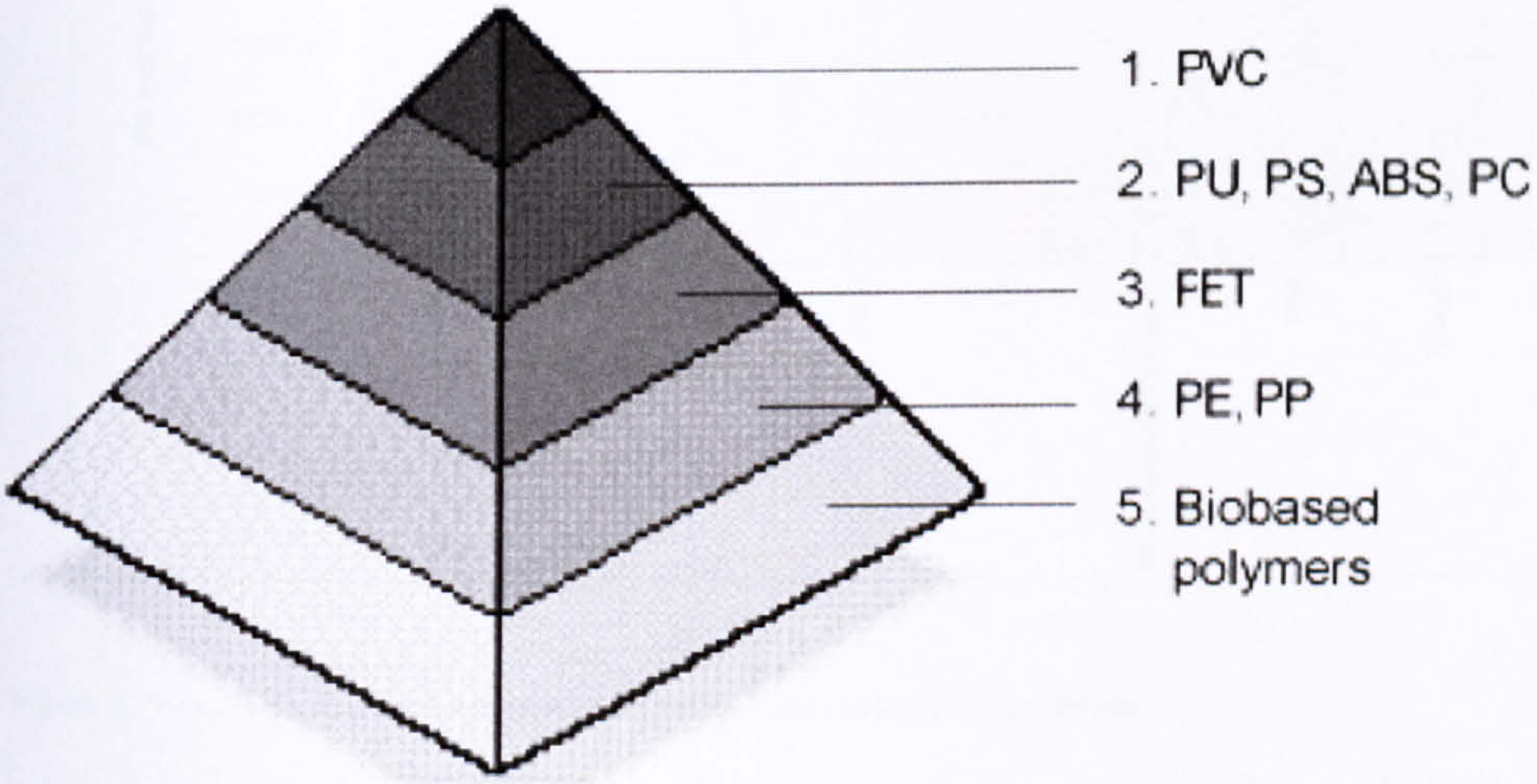


Figure 7 Green Peace's poisonous plastics pyramid [5]

The pyramid claims to rank plastics in terms of their harmfulness to the environment. Green Peace consider PVC to be the least eco-friendly as chlorine is used in its production. This is however, a very simplistic view, and could be deemed as misleading in some cases. A more extensive evaluation considering all environmental factors from cradle to grave may provide a more informative result.

Materbi SGC 2763 and Wells Plastics biodegradable additive BD92397 have so far only been lab scale trailed, Materbi SGC 2763 was successful, however high costs, see Figure 8 for a cost comparison, have prevented any further trialing.

The Wells Plastics biodegradable additive BD92397 was combined with Pactiv's current commercial grades of Polypropylene (PP) and trialed in a Polyvinyl chloride lab scale trial extruder. Figure 6 shows that the trial was not a 100% success as the additive burnt during extrusion, and poor dispersion is clearly visible. A further trail is scheduled on a more appropriate PP extruder.

Further materials will be investigated further as and when they become commercially available.

2.2 Development of Novel Starch based materials

The incorporation of starch into commodity plastics, with a view to the starch enhancing the biodegradability of the material, has generated world wide interest. This is for a variety of reasons including starch being the cheapest biopolymer. Figure 8 shows how expensive current biodegradable polymers are.

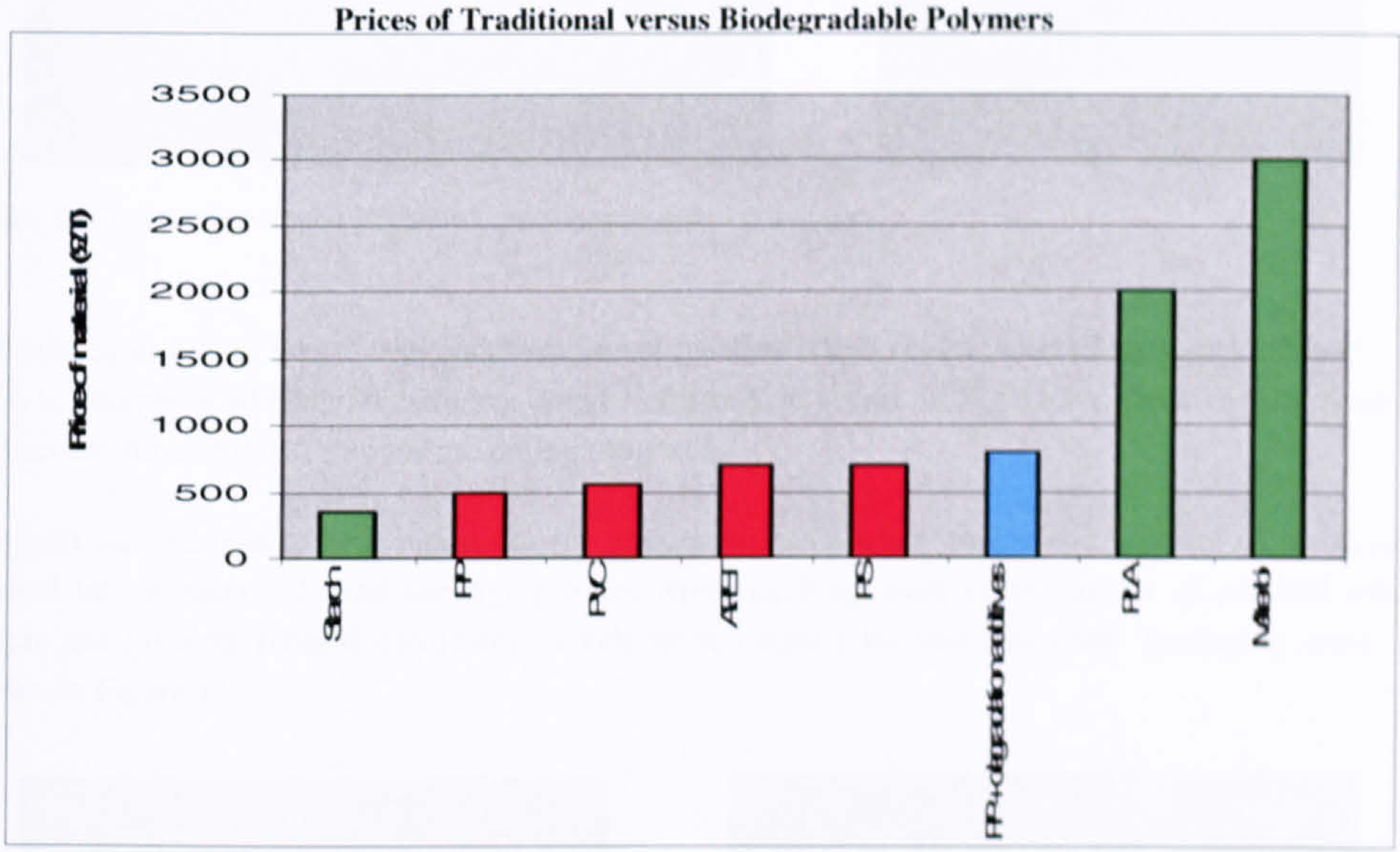


Figure 8 Price (£) per tonne comparison of traditional and biodegradable polymers

Initial research showed that 100% wheat starch could be successfully extruded as shown in Figure 9.0.

Figure 9 Initial trailing proving that 100% starch could be extruded

Different approaches exist that use starch for the production of tailored materials.

Pactiv UK thermoforming is particularly interested in rigid materials. Initially the research will focus on materials that can be extruded and thermoformed on existing machinery.

Trialing was carried out at Brunel University, to determine whether Starch combined with PVA has the potential to form an extrudate, which in turn could be thermoformed into a tray for food purposes.

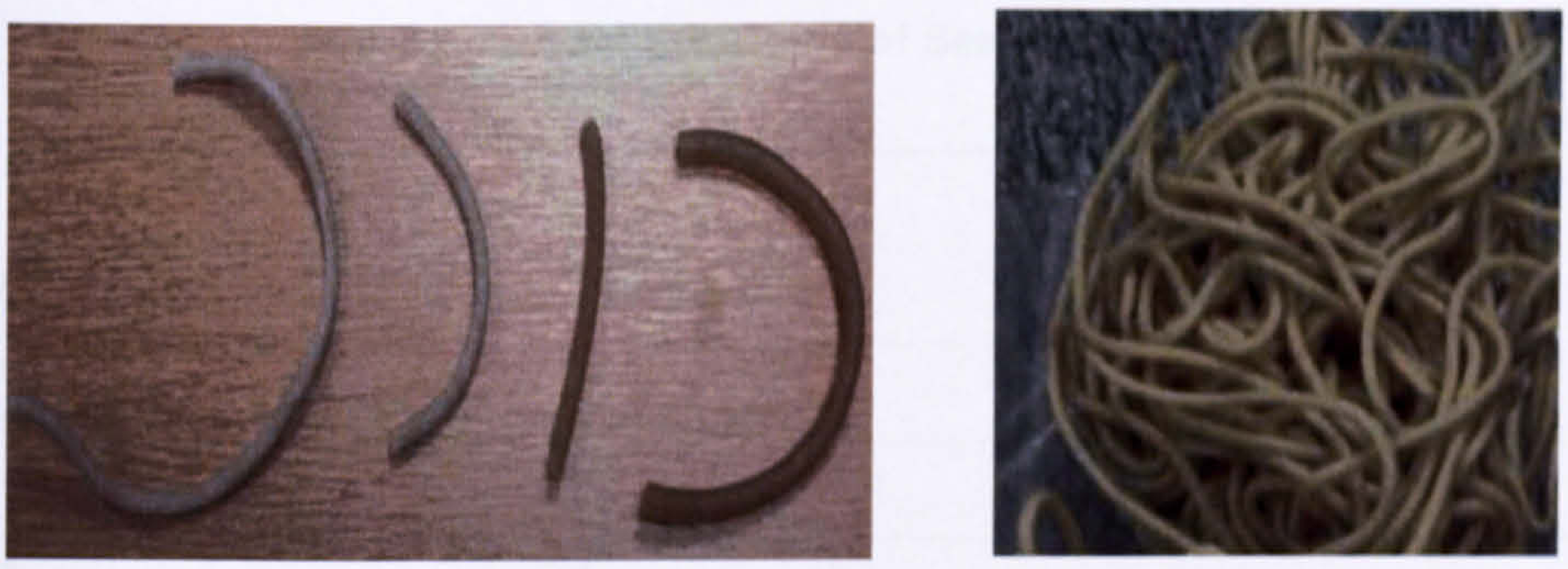


Figure 10 Comparison of the PVA/starch combination and 100% starch

The subsequent stage was to trial combinations of purified wheat starch, wheat starch, glycerol and PVA to determine whether an extrudate could be formed, as shown in Figure 10, which in turn could be vacuum formed into a tray for packaging purposes.

The trial was deemed to be a success as the combinations of wheat starch and glycerol were vacuum formed into a pasta coloured packaging trays. More exciting were combinations of purified wheat starch and glycerol formed extrudates, which were vacuum formed into **clear** packaging trays, as shown in Figure 11.

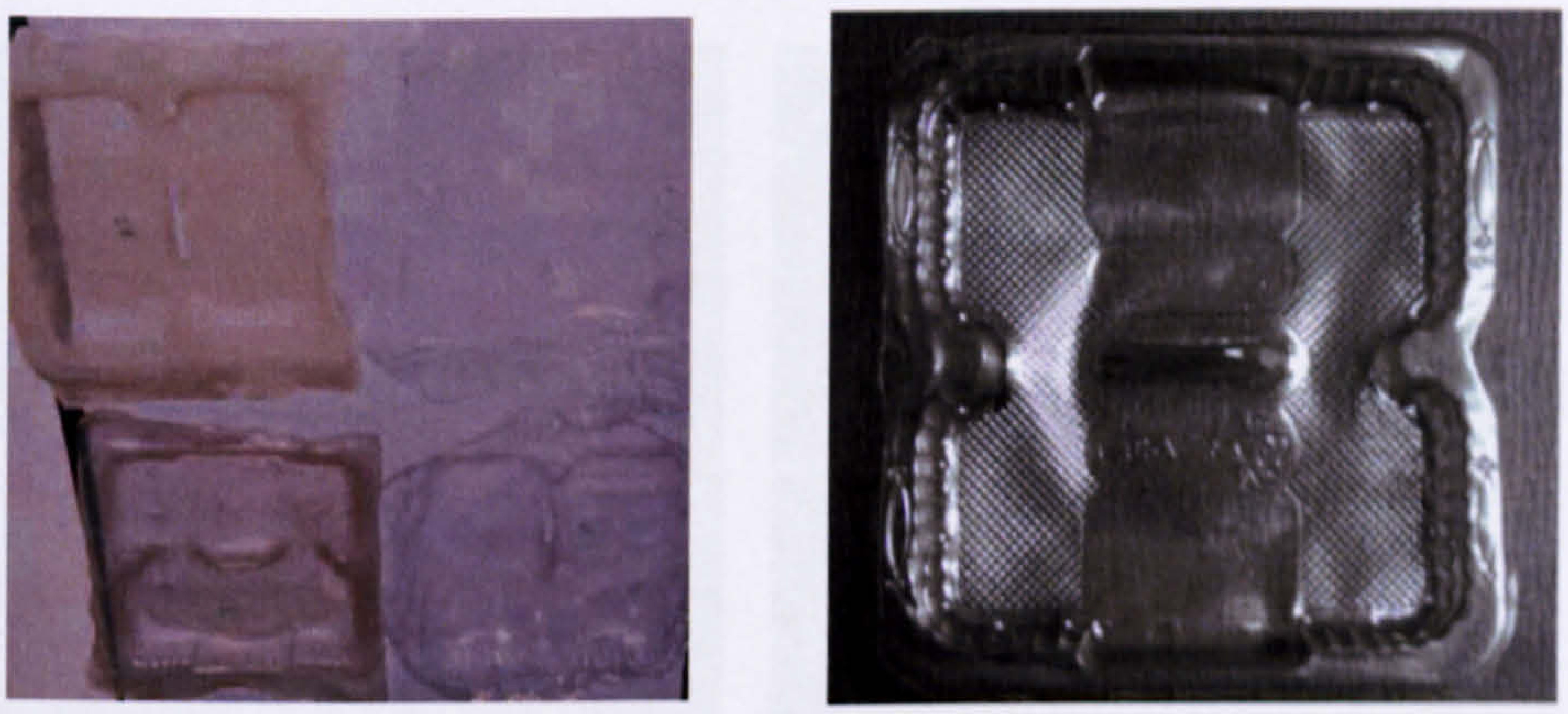


Figure 11 Wheat Starch/ Glycerol combination, a pasta coloured packaging tray (left) and Purified Wheat Starch/ Glycerol combination, a **clear** packaging tray (right).

Unfortunately, the mechanical properties of the purified wheat starch and glycerol combination were found to be lower than for conventional oil based plastics such as Polypropylene. The highest impact strength of the notched samples for example is 2.73 KJ/m^2 compared to the average impact strength of Neste Chemicals N.V grade of polypropylene which is 15.52 KJ/m^2. Figure 12 highlights that the average impact strengths of the (notched) purified wheat/ glycerol combinations are, at least, 5.68 times lower than that of conventional oil based Polypropylene (PP). The highest recorded individual impact strength was 5.52 KJ/m^2 and had there not been cracks formed during the extrusion process, as shown in Figure 13. However the average impact strengths would still have been approximately 3 times lower than that of PP. Further mechanical testing and composting tests are currently being carried out.

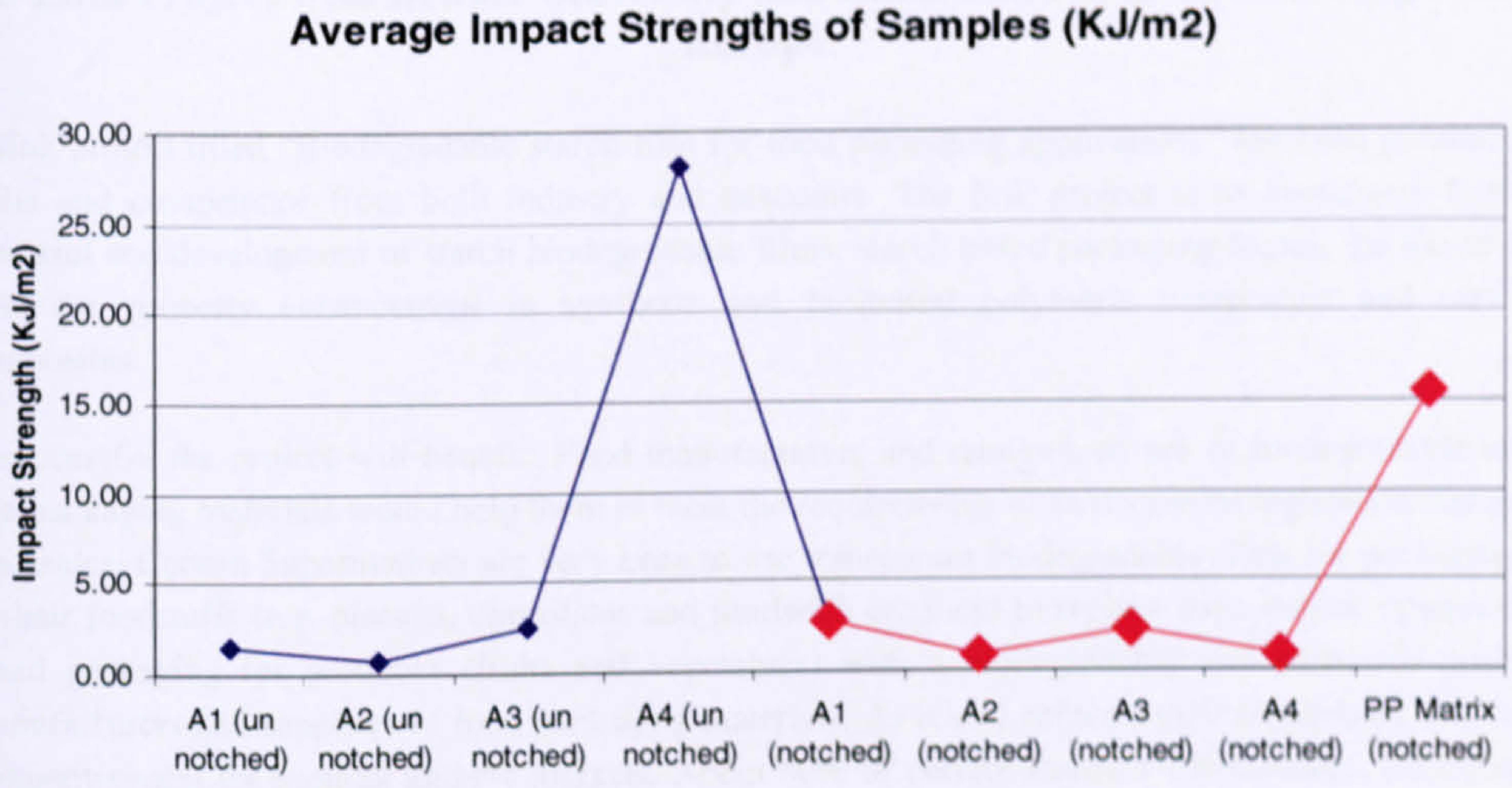


Figure 12. Graphic representation of average impact strength from impact testing of notched and unnotched samples.

Further work will investigate the potential of adding additives, for example aliphatic additives and natural rubber, to enhance the mechanical properties, such as impact strength.

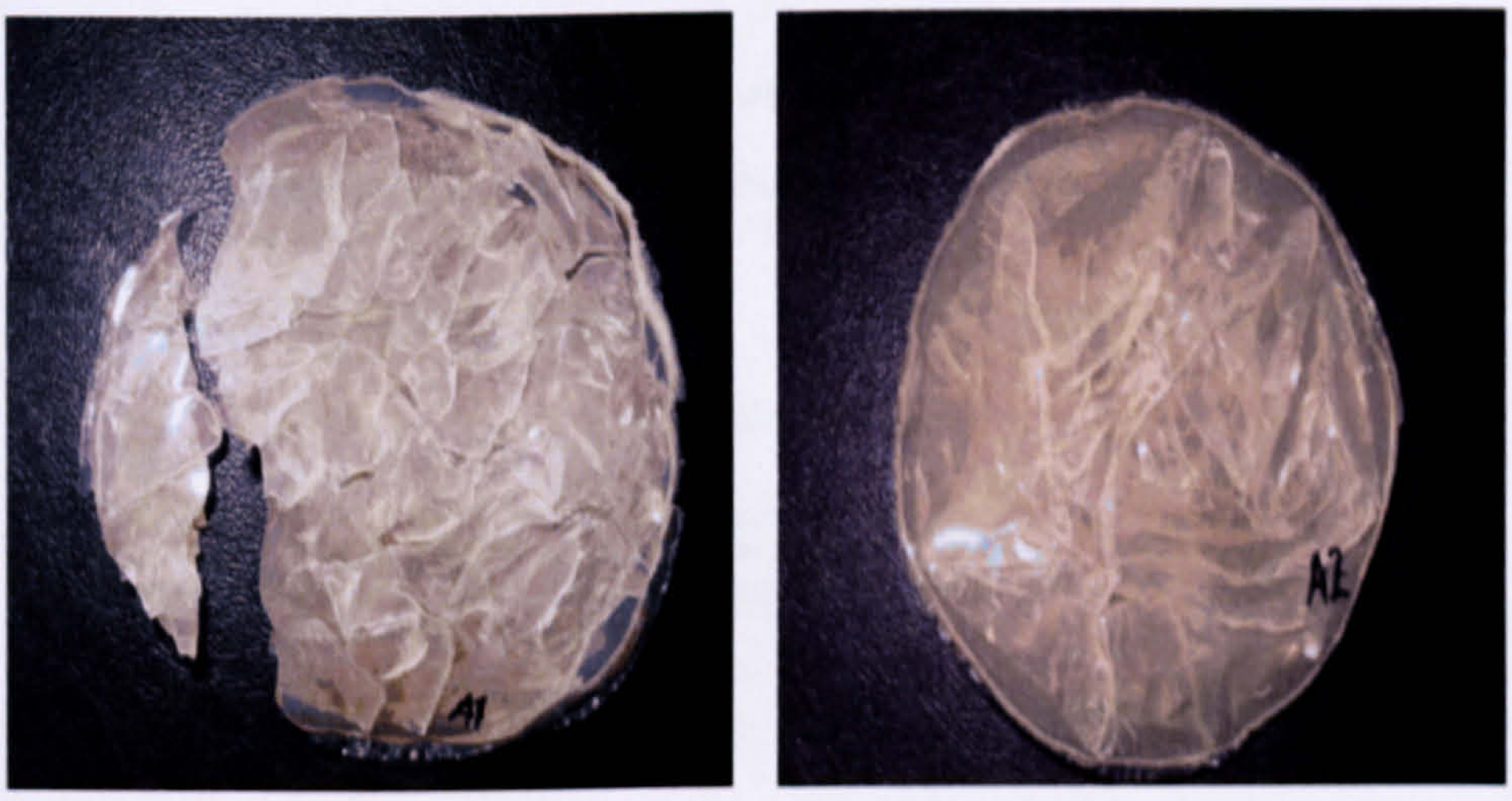


Figure 13: Images of the purified wheat starch and glycerol extrudate samples similar to those used for impact testing

The issue of the wheat starch extrudate going mouldy when stored in plastic bags, as shown in Figure 9, also needs to be addressed, however this was not observed with the purified wheat starch. Further trialing will be concentrated around using the purified wheat starch rather than the wheat starch.

This does however raise the issue of cost, as the purified wheat starch is more expensive when compared to the wheat starch this needs to be taken into consideration, as this is to be a low cost solution.

2.3 Link Project with Brunel University and Industrial Partners including Pactiv Europe

A link project titled "Biodegradable starch film for food packaging applications" has been proposed using skills and competence from both industry and academia. The link project is to investigate further the potential and development of starch biodegradable films, starch based packaging foams, the use of natural fibre for property enhancement in synthetic and bio-based polymeric composites and clay nano-composites.

If successful the project will benefit: Food manufacturers and retailers, as use of biodegradable and GM free packaging materials would help them to meet the requirements of environment legislation and enhance their sales. Certain Supermarkets are very keen to use transparent biodegradable films for packaging many of their foodstuffs (e.g. biscuits, chocolates and sandwich etc.) and to replace their current opaque plastic-based packaging for produces (fruits and vegetables) with a biodegradable and economic alternative; Manufacturers and suppliers of food packaging materials. As it will enhance their technology and business competitiveness by opening up new markets. About 80% of current Pactiv's UK business, for example, is in the provision of plastic sheet food packaging materials made by thermoforming and biodegradable products would be a significant step forward, in environmental terms, commanding a reasonable margin over plastic based packaging; British cereal growers and starch suppliers, as it will stimulate the acquisition of starch as alternative industrial materials; The down-stream food packaging converters as they can tailor the biodegradable starch based film/sheet to purpose-designed packaging; and the general public for improvement of their quality of life, as the materials would lower the environmental impact.

Acknowledgements

The author would like to thank the EPSRC and Pactiv Europe for funding this project and acknowledges the assistance given by Dr Jeremy Tonkin and Dr Jim Song.

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APPENDIX B: PAPER SUBMITTED TO POLYMER DEGRADATION AND STABILITY OCTOBER 2006

Assessment of Biodegradable Packaging Materials under Simulated Home Composting Conditions.

Running title: Biodegradable Packaging in Home Composting Conditions.

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Abstract

Various packaging materials were assessed in a simulated home composting study. Whole food service/packaging items and small specimens were incorporated into a base-mixture of green garden waste and exposed to low temperature composting (8 – 25°C) for up to six months in the field. Degradation of the materials was assessed by visual inspection for fragmentation and incorporation into the developing compost and as mass loss. Three groups of biodegradability behaviour were identified: fast degrading materials (primarily starch-based polymers), medium rate degraders (primarily plant fibre materials) and slow degraders (primarily oil-based polymers and PLA). The majority of composts derived from the study provided suitable growth media for tomato plant development in accordance with the PAS 100 (2002) protocol. It was concluded that biodegradability assessed under high temperature industrial composting evaluations does not provide suitable information for the evaluation of behaviour in home (low temperature) composting systems.

Keywords : Biodegradable polymers, packaging, composting, mass loss, seed germination

Introduction

There is currently strong interest in the development of packaging materials that have reduced environmental impacts over their whole life cycle compared with 'conventional' materials. This reduced impact can be achieved through a reduction in the energy and resources required to manufacture and use the materials, by a shift from fossil fuels to renewable resources and development of materials that offer alternative end-of-life disposal options. In the latter case, much interest has been shown in biodegradable packaging materials that can be disposed of by composting. Typically, such materials are made from renewable raw materials such as starch or cellulose. This end-of-life aspect of packaging materials is regarded as particularly significant in view of the recent recognition of waste generation and waste management as important environmental aspects of present day society [1].

At the end of their useful life, used packaging materials enter various waste streams. It is estimated that 67 million tonnes of packaging waste are generated annually in the EU and much of this enters the municipal solid waste stream, accounting for approximately one third of all EU municipal solid waste [2]. Municipal waste includes household waste such as food packaging, which at present is made predominantly from non-biodegradable oil-based plastics. These are difficult to reuse or recycle once material types are mixed. Indeed in the UK only 5% of plastics in the household waste streams are recycled, the majority of the remaining 95% ends up predominantly in landfill [3].

A biodegradable polymer is capable of being degraded by micro-organisms. In order to be termed biodegradable it must loose both the mechanical and the chemical identity of the polymeric starting material, usually within a given time period. In order to achieve this, biodegradable polymers need to have hydrophilic end-groups such as oxygen and nitrogen [4].

To be designated as recoverable by composting, a material has to demonstrate biodegradability and disintegration in a composting system. This will usually be in compliance with standard test methods. In Europe, criteria for composting and biodegradability are set out in the European standard EN 13432 (2000) for industrial composting [5]. Performance in accordance with EN 13432 means that the packaging material complies with the requirements of the EU Directive on Packaging and Packaging Waste (94/62/EC). The standard EN 13432 specifies the following four requirements and procedures that packaging and packaging materials must fulfil in order to determine their compostability:

1. Biodegradability: More than 90% biodegradation must be achieved compared to standard cellulose. This must be achieved in less than 180 days under controlled composting conditions as stated in ISO 14855 [6].
2. Disintegration during a biological waste treatment process: More than 90% of the original dry weight must pass through a >2mm fraction sieve.
3. Effect on the biological treatment process: absence of hazardous chemical.
4. Effect on the quality of the resulting compost: need to test for ecotoxicity using reference compost, for example, a seed germination test.

It should be noted that EN13432 refers to the process of industrial composting and does ***not*** indicate that a given material would be compostable or biodegradable in a home composting system.

In countries such as the UK where landfill is currently the main waste management strategy, food packaging materials have considerable potential to reduce environmental impacts and help meet EU directives on waste management. However, whilst such materials can be designed for biodegradability, their suitability for various waste streams has yet to be explored in detail. An obvious potential environmentally friendly option for biodegradable packaging is for consumers to incorporate them into domestic composting systems, as this disposal option requires little infrastructure or transport, which cannot be said of other disposal routes.

This research was conducted to determine the extent of biodegradation that can be expected when biodegradable or potentially biodegradable packaging materials are disposed of in simulated home composting. The main aim of the study was to establish whether potentially biodegradable packaging materials would show appropriate levels of biodegradation when home composted together with green garden waste. Biodegradation was assessed according to material weight loss over a 24 week winter/spring period between November and May in the South East of the UK. The studies were conducted on whole units of food packaging and small specimens of a wider range of materials, with the main emphasis placed on identifying the performance of a potato starch-based packaging tray material (starch), a wood pulp cellulose-based disposable plate (paper) and a maize starch-based poly-lactic acid (PLA) packaging tray material.

Materials and Methods

Two studies were carried out consisting of exposing materials for biodegradation in the composting system. The first study used *whole units* of food packaging manufactured from 3 different materials. The second used *small specimens* of 12 bio-based materials all of which either are or have the potential to be used in the food packaging industry. The 3 'main' material types were a potato starch (starch), a pressed wood pulp paper (paper) and polylactic acid (PLA).

Packaging materials

The packaging materials used are given in Table 1. Six of these were derived from materials used commercially and six were derived from experimental materials designed to be biodegradable.

Composting system and monitoring

A 160 litre home composter 'bin' system was used for the composting trials (Figure 1). The composter bins were placed directly on the soil/grass surface in an unshaded field at the Imperial College London, Silwood Park, Ascot, Berkshire, UK. The composters were filled with a 'base mixture' of approximately 60% green herbaceous and grass clippings and 40% chopped 'woody' herbaceous material from the local site, all free of any pesticides or herbicides. Added to this base mixture in the composter were either:

i) sample racks of stainless steel mesh containing replicate small specimens (approximately 25 mm x 25 mm x material thickness (occasionally folded)) of all 12 packaging materials, or

ii) 6.4 wt % of one of the 3 main packaging materials as whole units mixed in with the green waste base mixture.

The sample racks were inserted approximately 600 mm below the compost mixture surface and the whole packaging units were distributed by mixing throughout the compost mixture (Figure 1). The small specimen test (i) was distributed across three different composter units with three replicate specimens removed per composter per sampling time. The whole units test (ii) was distributed across two composters per material type and five whole units were extracted at each sampling time. Two composter bins containing only the compost base mix and no added biodegradable packaging materials were used as controls.

The composters were set up in October 2004, allowed to establish for 4 weeks before the packaging materials were introduced in November 2004. The composters were then sampled on an approximately monthly basis from November 2004 to May 2005 for temperature and overall volume reduction. Replicate samples of the test materials were removed for visual inspection, mass loss and moisture content determination. After six months a final inspection of the resulting composts from the whole unit composters was made and compost samples removed for a seed germination trial.

Packaging materials – sample preparation and exposure

A weight loss methodology was used to establish the rate of polymer degradation. Whole units were mixed in with the green waste base mixture and were added at a rate of 6.4% by mass of the base mix. For the small specimen study, replicate pre-weighed polymer specimens were individually secured into nylon mesh bags and placed into a stainless steel rack for easy retrieval. The racks were buried in the middle of a composting bin between layers of base mixture that had previously been composted for 30 days to establish an active microflora/fauna. Approximately every 30 days, up to 180 days, the racks were removed and sets of polymer specimens retrieved for degradation assessment. Racks with remaining specimens were re-buried for subsequent specimen removal. Additionally, prior to each sampling event, temperature readings were taken from the upper, middle and base locations in each composting bin to evaluate composting temperature over the time period.

Assessment of biodegradation and moisture content

Visual assessment: This was conducted on the whole units of the 3 main materials to obtain a general assessment of the extent to which the materials showed signs of moisture pick up, microbial attack, grazing or other breakdown, fragmentation and loss of integrity in order to evaluate integration into the compost matrix. A combined ranking scale with five levels from “no degradation” to “complete integration into compost” was used to express results (Table 2).

Moisture content and mass loss: At each sampling time for the whole unit study all the compost was removed from one of the composting bins and five whole units of the packaging material were retrieved from the compost as intact as possible and their appearance recorded. They were then individually weighed whilst wet, and again after oven drying at 105°C for 24 hrs. The moisture content and mass loss per whole unit was then calculated and compared to an average value for that type of whole unit (established from previous weighings of 50 representative whole units, corrected for initial material moisture content). For the small specimens, after removal from the packets and visual inspection, the specimens were weighed ‘wet’ and after oven drying for 24 hrs at 105°C. Moisture content (dry wt basis) and mass losses were calculated by comparison with the initial values for each specimen prior to test (after correction for initial moisture content). Data for material weight loss was averaged and standard deviations calculated.

Seed germination and seedling development in resulting composts (PAS 100)

A bioassay of the composts from the whole unit test and the control compost was conducted in accordance with the Publicly Available Standard (PAS) 100 (2002) 'Specification for composted materials' [7]. PAS 100 is intended for composts which result from source segregated biodegradable materials and specifies the minimum quality of compost needed to reduce any risk to humans, animals, plants and the environment to acceptable levels. F1 tomato seeds (variety Shirley, Sutton Seeds, UK) were placed in the prescribed mixture of background growth medium and test compost in seed trays and maintained with regular watering at a temperature of 20 – 25°C in a naturally light greenhouse in early summer 2005 over the 28 day period of the test. Seed germination, fresh plant mass, abnormalities and weed emergence were recorded in accordance with PAS 100. The assessment of weed propagules is relevant to an industrial compost process as part of a commercial product quality assurance but, due to the low temperatures attained in domestic composting, the sterilisation of such propagules is not a target for such systems.

Results

Visual assessment and bulk degradation profile of the composters

The temperature profile in the compost bins (Figure 2) showed that the systems were functioning as a low temperature composting environment between 15 to 18°C in November at the start of the experiment. This profile dropped to a low of approximately 8 - 10 °C in Jan/Feb/March and then rose to approximately 14 °C in May. The lowest composter bin temperatures reflect the typical lower winter temperatures in January and February in the South East of the UK. All composter bins showed an acceptable level of reduction in biomass volume during the composting period equating to about half of the original volume (Figure 3). The temperature profiles of the bins and the degradation of their contents was largely consistent across the whole study. The type of content (whole units of any type or racks of small specimens) did not make a significant impact although the 2 composter bins with PLA whole units (trays) showed the lowest volume reductions (30-40% reduction).

The results of visual assessment of the whole units and their integration into the compost matrix during the composting process are summarised in Table 2. In general, the breakdown of the small specimens was very similar visually to that of the whole units, although it tended to be not as extensive as in the whole units. This is likely to be due to some protective effects of the mesh packets and racks.

Visual assessments of the whole units clearly demonstrated that complete disintegration and incorporation of the starch trays into the compost matrix had occurred after 90 days of composting. The paper plate material was also extensively broken down over the composting period, although it was possible to distinguish elements of the original plate material after 180 days, despite their being heavily discoloured and lacking structural integrity. The PLA polymer showed no visual evidence of microbial breakdown after 180 days, although fragments had broken off some trays. This was not considered to be disintegration as a result of biodegradation but was attributed to disturbance of the bins and mechanical damage when retrieving samples.

Mass loss and moisture content

Mass loss and moisture content

The results for determinations of mass loss (extent of biodegradation) for the 3 main material types (Starch, paper, PLA) are given in Figures 4 and 5 for whole units and small specimens respectively. The data for the full range of material types as small specimens are presented in Figure 6.

During the first two months of exposure of the whole units, two groups of materials could be identified: those exhibiting biodegradation (15 – 30 % mass loss) and those with no biodegradation (>5% mass loss). After approximately 3 months exposure, three types of degradation behaviour could be distinguished: the potato starch material exhibiting mass loss of < 80%, the pressed paper material had a mass loss of 30% and PLA had very low mass loss of > 5%. This separation of 3 clear groups then continued to the conclusion of the experiment at 180 days, with the readily biodegradable starch material becoming indistinguishable from and fully incorporated into the compost matrix. The pressed paper showed extensive degradation but remained recognisable on close inspection. The PLA was clearly recognisable as such and showed no evidence of incorporation into the compost.

The experiment was also conducted using small specimens of the same materials and very similar results observed with 3 'classes' of behaviour (Figure 5). In this case, absolute levels of degradation in the starch material were initially slightly higher than with the whole unite although final levels of biodegradation were slightly lower than in the whole unit study. Paper showed a more rapid initial breakdown and PLA exhibited less breakdown than with the whole units (the whole units of PLA were probably mechanically damaged in the whole unit study). Overall there was a high degree of consistency in results form the small specimens and the whole units.

Examination of the data for the full range of materials in the small specimen study confirmed that the biodegradation behaviour fell into 3 classes (Figure 6). During the first month, two groups of polymers could be easily recognised – those exhibiting 30 – 40% weight loss and those with apparently no biodegradation (>5% mass loss). Beyond approximately 4 months exposure, three groups of polymers could clearly be distinguished: the fast degraders (starch-based polymers and Silvergrass) exhibiting mass loss of < 80% , the medium degraders (paper and coconut fibre) with mass loss of approximately 45% and the slow degraders (PLA, polypropylene with additives and starch/PCL) with very low mass loss > 5%. This differentiation of 3 clear groups then continued to the conclusion of the experiment at 180 days, with the readily degradable materials becoming indistinguishable from their sealed packets. The middle group showed extensive degradation but remained recognisable on close inspection. The slow degrading materials were clearly recognisable as such and showed little or no degradation.

The results for moisture content assessment (Figures 7 & 8, Table 3) showed that fast and medium rate degraders absorbed moisture readily during the composting process (range from 50 to 400% mc over the measurable time period). The slow degrader group exhibited very low levels of moisture absorption (typically < 40% mc and in the case of PLA <5% mc).

Seed germination of final composts

The results of the PAS 100 bioassay (Table 4) show that all composts from the whole units (starch, paper and PLA) compost bins and from the composted base mix (control) gave equal or higher seed germination results compared to the growth medium base (PRGM). Furthermore all the 'amended' composts, with the exception of Bin 1 of PLA, gave equivalent or better fresh seedling masses (a 20% reduction in above ground seedling fresh mass relative to the PRGM control result. PLA Bin 1 had a 21% reduction in above ground seedling mass). All the amended composts failed the weed criterion of PAS 100 but this is expected because low temperature composting systems do not achieve sterilisation of weed seeds.

Discussion

This study has shown that several biodegradable packaging materials exhibited biodegradable properties in simulated home composting systems when assessed according to mass loss and visual inspection of disintegration and incorporation. The very close similarity of results between materials placed in the compost system as whole units and as small specimens in nylon packets also indicates that small specimens can provide relevant data to assess the levels of biodegradation that can be expected from full-scale materials. The home composting system used here operated over a temperature range of approximately 5 – 18°C for 6 months and achieved a compost volume reduction of approximately 50%. The materials that were identified as readily compostable in this home composting system were predominantly based on high levels of starch although the pressed silvergrass (*Miscanthus*) pulp material was a grass fibre/starch composite.

A second group of materials was identified in the study - the so called medium degraders. These were based on plant fibres and exhibited mass losses of approximately 50% over the 6 month low temperature composting period. The extent of degradation in these materials over this period and the easily fragmentable nature of the residual material the end of the period indicates that these would be acceptable for home composting. They are readily incorporated into the compost matrix after approximately 4 to 6 months of low temperature composting. The third group of materials identified, the slow degraders, exhibited no or very low levels of biodegradation or fragmentation over the composting period. It is known that elevated temperature, for example 60°C, can be an important parameter enabling the induction of biodegradation of polymers such as PLA [8-10]. Such temperatures are clearly lacking in the home composting system and even prolonged exposure over 6 months did not lead to evidence of biodegradation. An exception to this was the starch/PCL material study in which mass loss began to be induced after 5 and 6 months of exposure (3 and 6% mass loss respectively) and this was associated with increased absorption of moisture at this time. In all cases of slow/no biodegradation the materials showed very low or zero moisture absorption during the earlier part or the whole of the composting period and this is clearly a factor limiting the induction of biodegradation.

It is interesting that three 'groups' of biodegradability behaviour in home composting were clearly recognisable from the data for both whole unit materials and small specimens. We interpret this as indicating that the materials types studied do segregate into a limited number of well defined categories and that this is associated with fundamental properties of these materials that affect their performance in low temperature biodegradation and composting. It appears most likely that readily biodegraded types such as the high starch materials (but also silvergrass/starch material) quickly absorb moisture and become amenable to microbial digestion which proceeds rapidly. Less easily attacked materials like cellulose paper and lignified plant fibres (e.g. coconut) also absorb moisture well but their degradation rate is limited by the accessibility of their polymeric structures to microbial digestion, which consequently proceeds at a slower rate. Finally, the low or non-degradable materials in this low temperature composting environment such as PLA are resistant to moisture absorption and have a molecular structure that does not enable microbial degradation. It appears probable that some materials in this latter category may become susceptible to microbial attack after prolonged exposure (e.g. starch/PCL composite) and that once started, microbial degradation is likely to proceed at a slow rate assuming conditions remain favourable.

The seed germination study using the methodology of PAS 100 has shown that composts made from green waste incorporating approximately 6% by mass of home composted starch or paper trays gives growth media that support good seed germination and seedling development. Similar results were also achieved with compost incorporating non-biodegraded PLA materials, although seedling fresh mass was somewhat reduced compared with controls. Similar, though greater reductions in seedling mass, in composts with degradable polyethylene and control composts from open windrow systems have been found by Davis *et al.*, [11].

It is apparent from this study that several biodegradable packaging materials can be processed in home composting systems and yield compost materials suitable for plant growth. This capability will enable such materials to be disposed of in well run home composting systems and result in waste diversion from municipal waste streams. However, we have also demonstrated that a number of packaging materials that will typically biodegrade well in industrial, high-temperature composting systems failed to biodegrade in the low temperature home composting environment.

At a practical level, and to avoid confusion for consumers, these results suggest that it is very important to clearly distinguish those biodegradable packaging materials that can be expected to perform well in home composting systems from those where biodegradation can only be expected in industrial composting systems. Labelling schemes and consumer information should support such a distinction and we would recommend that the 'default' setting for a material to be defined as biodegradable and compostable should apply to materials that can show such behaviour in both home *and* industrial composting. Those that will only biodegrade in industrial composting systems (e.g. as shown by compliance with EN 13432) should be defined as 'industrially compostable'.

Acknowledgements

The author would like to thank and acknowledge the support given by Professor Jim Song, Brunel University and Dr Richard Murphy, Imperial College, London. The Engineering and Physical Sciences Research Council (EPSRC) for funding the Engineering Doctorate (Eng D) project carried at Brunel University and Pactiv UK.

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CAPTION LIST

Figure 1	Diagram of compost bin assemblies
Figure 2	Temperature profiles (°C) in compost bins
Figure 3	Volume reduction (%) in compost bins
Figure 4	Whole Units: mass loss (%) over time
Figure 5	Small specimens: mass loss (%) over time (starch, paper, PLA)
Figure 6	Small specimens: mass loss (%) over time (all materials)
Figure 7	Small specimens: moisture content (%) over time
Figure 8	Whole units: moisture content (%) over time

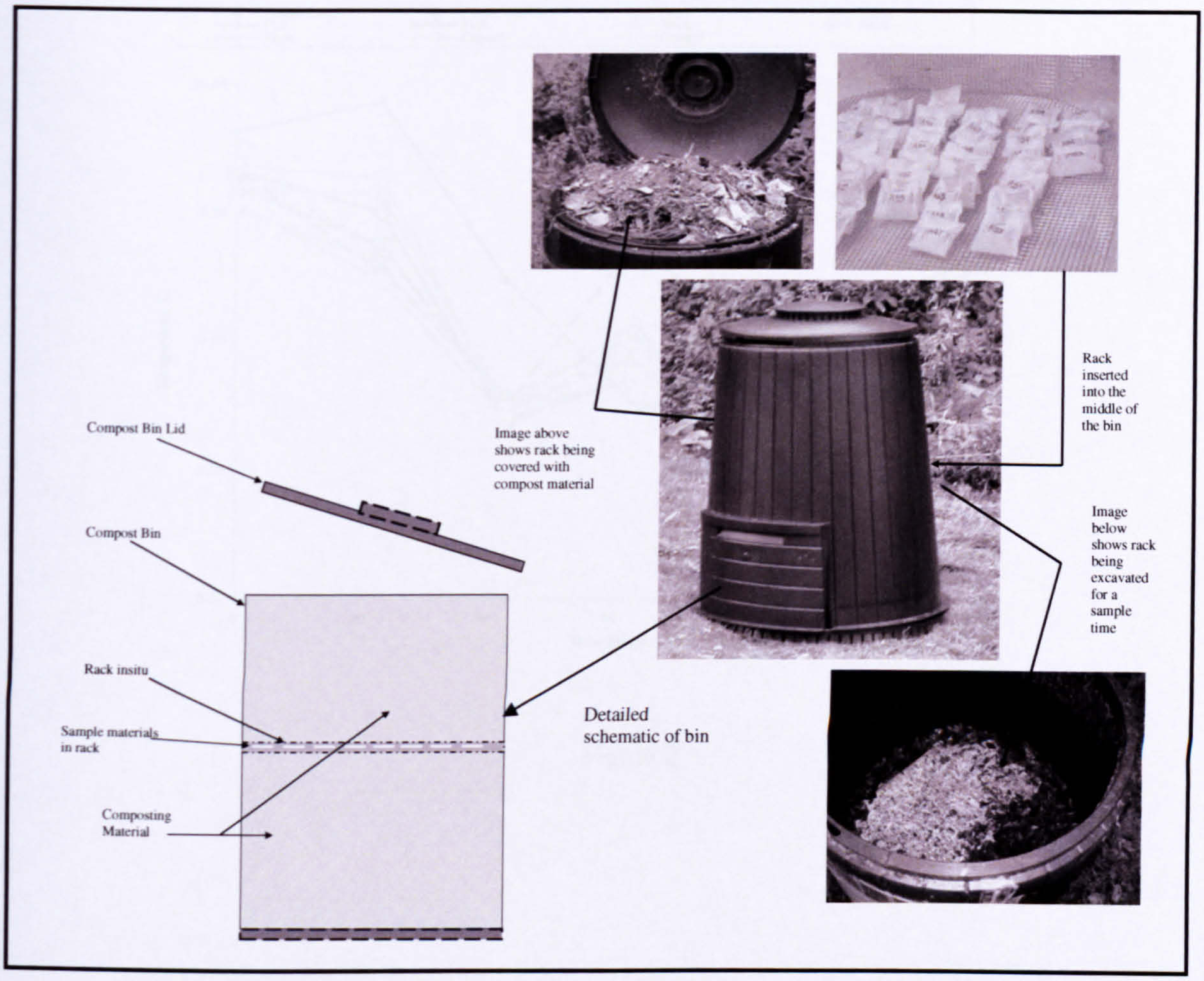

Compost Bin Lid
Compost Bin
Rack insitu
Sample materials in rack
Composting Material
Image above shows rack being covered with compost material
Detailed schematic of bin
Rack inserted into the middle of the bin
Image below shows rack being excavated for a sample time

Figure 1

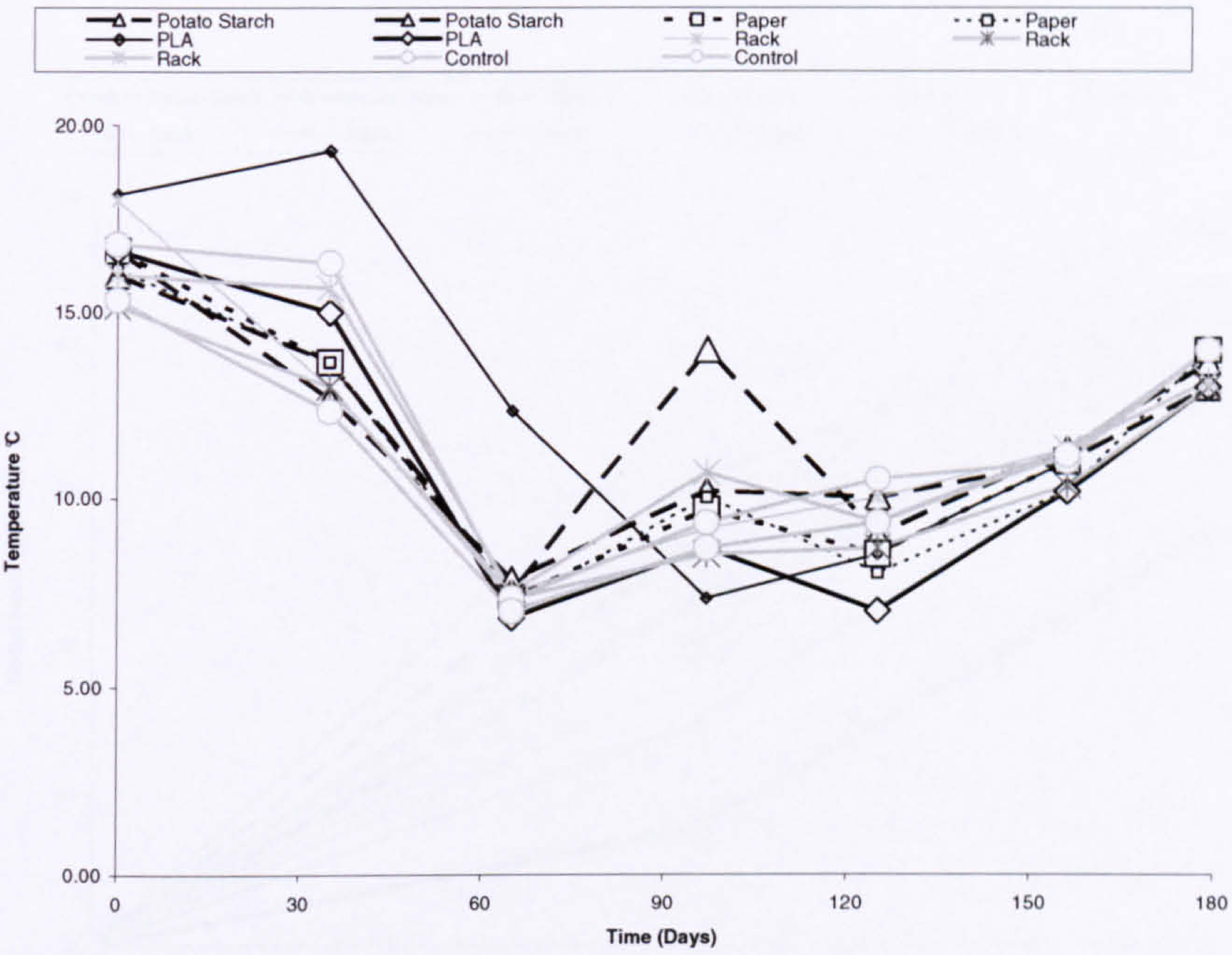

Potato Starch
PLA
Rack
Potato Starch
PLA
Control
Paper
Rack
Control
Paper
Rack
20.00
15.00
10.00
5.00
0.00
Temperature °C
0
30
60
90
120
150
180
Time (Days)

Figure 2

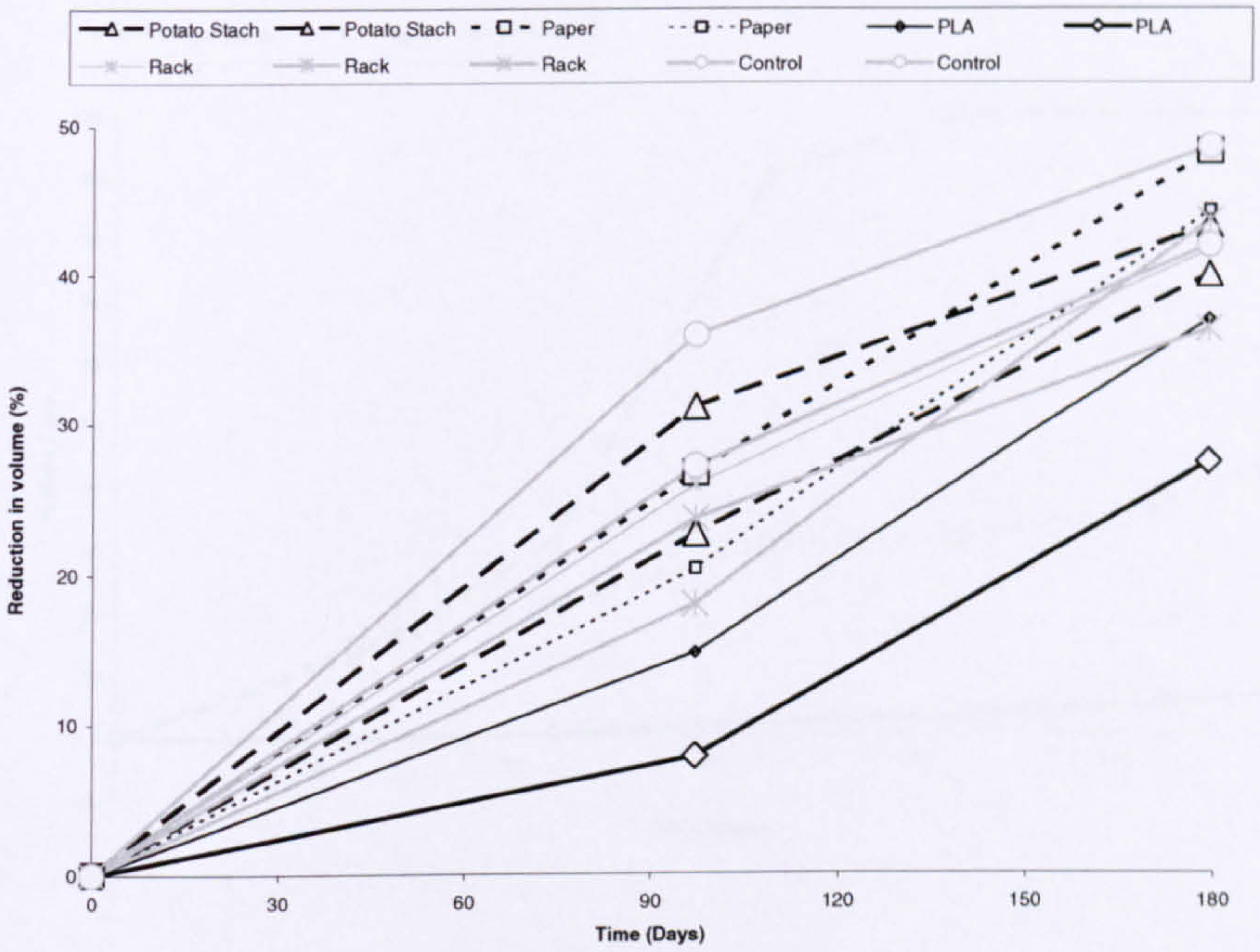

Potato Stach
Potato Stach
Paper
Paper
PLA
PLA
Rack
Rack
Rack
Control
Control
50
40
30
20
10
0
Reduction in volume (%)
0
30
60
90
120
150
180
Time (Days)

Figure 3

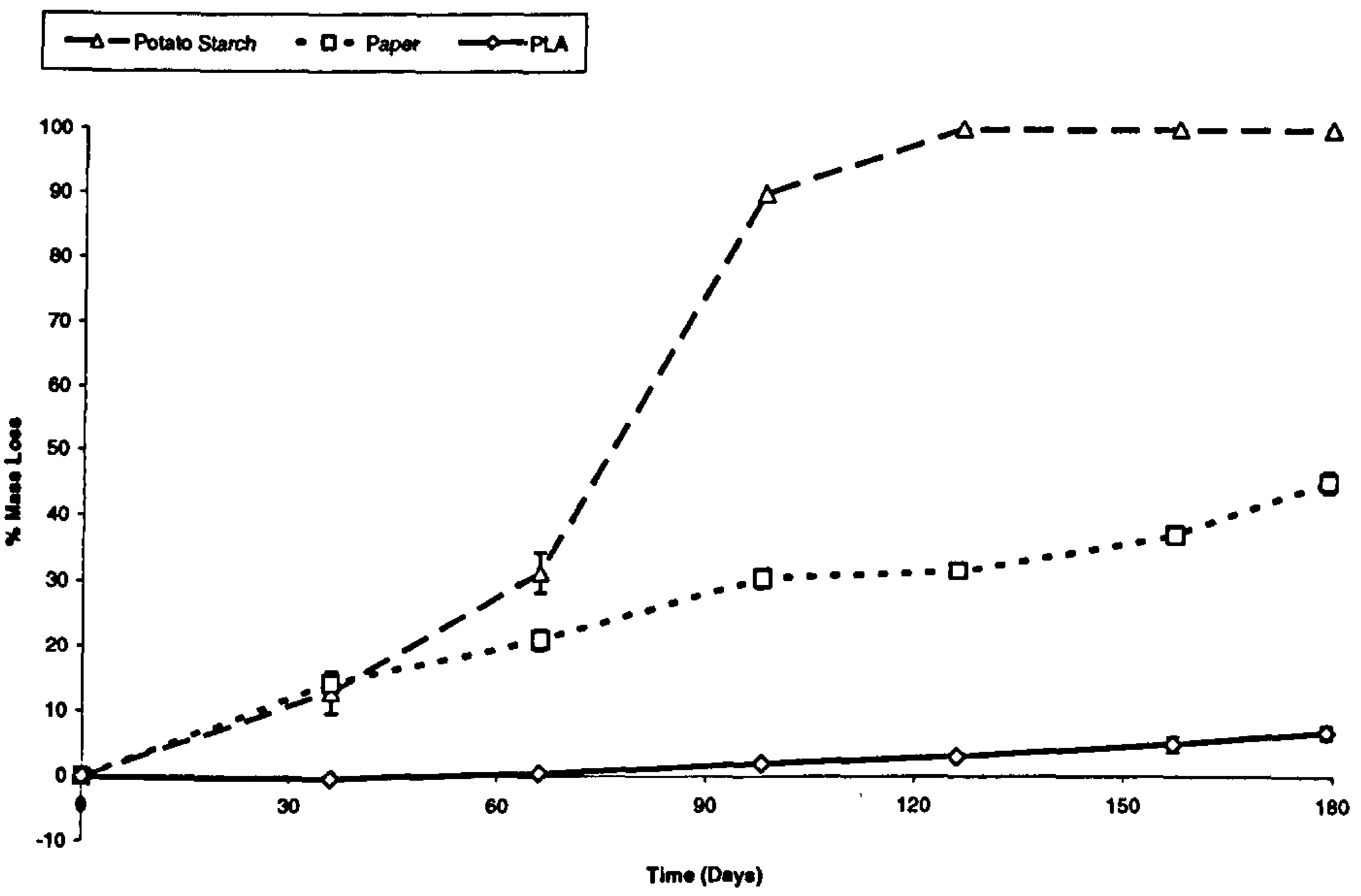

Potato Starch
Paper
PLA
% Mass Loss
100
90
80
70
60
50
40
30
20
10
0
-10
30
60
90
120
150
180
Time (Days)

Figure 4

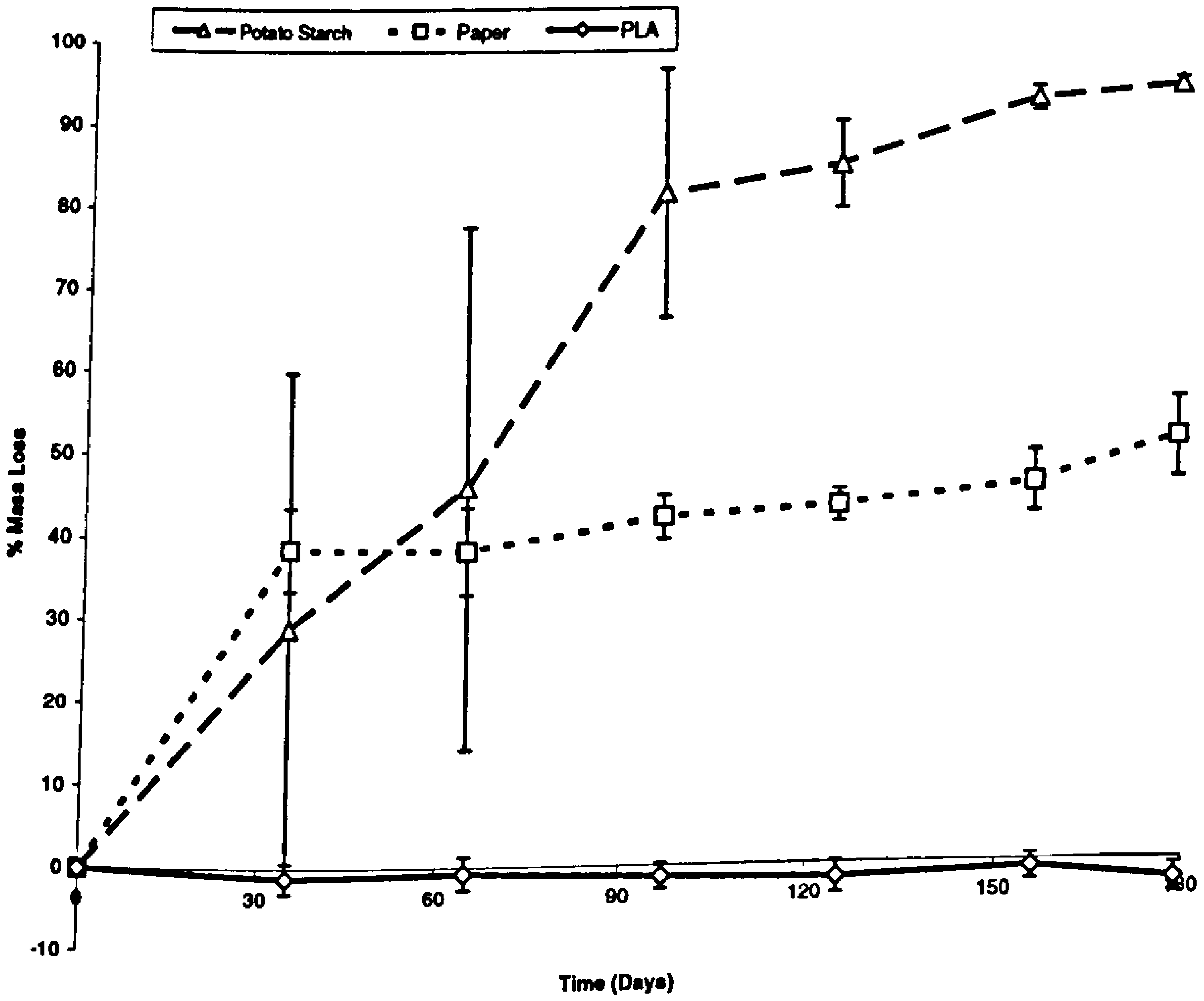

Potato Starch
Paper
PLA
% Mass Loss
100
90
80
70
60
50
40
30
20
10
0
-10
0
30
60
90
120
150
180
Time (Days)

Figure 5

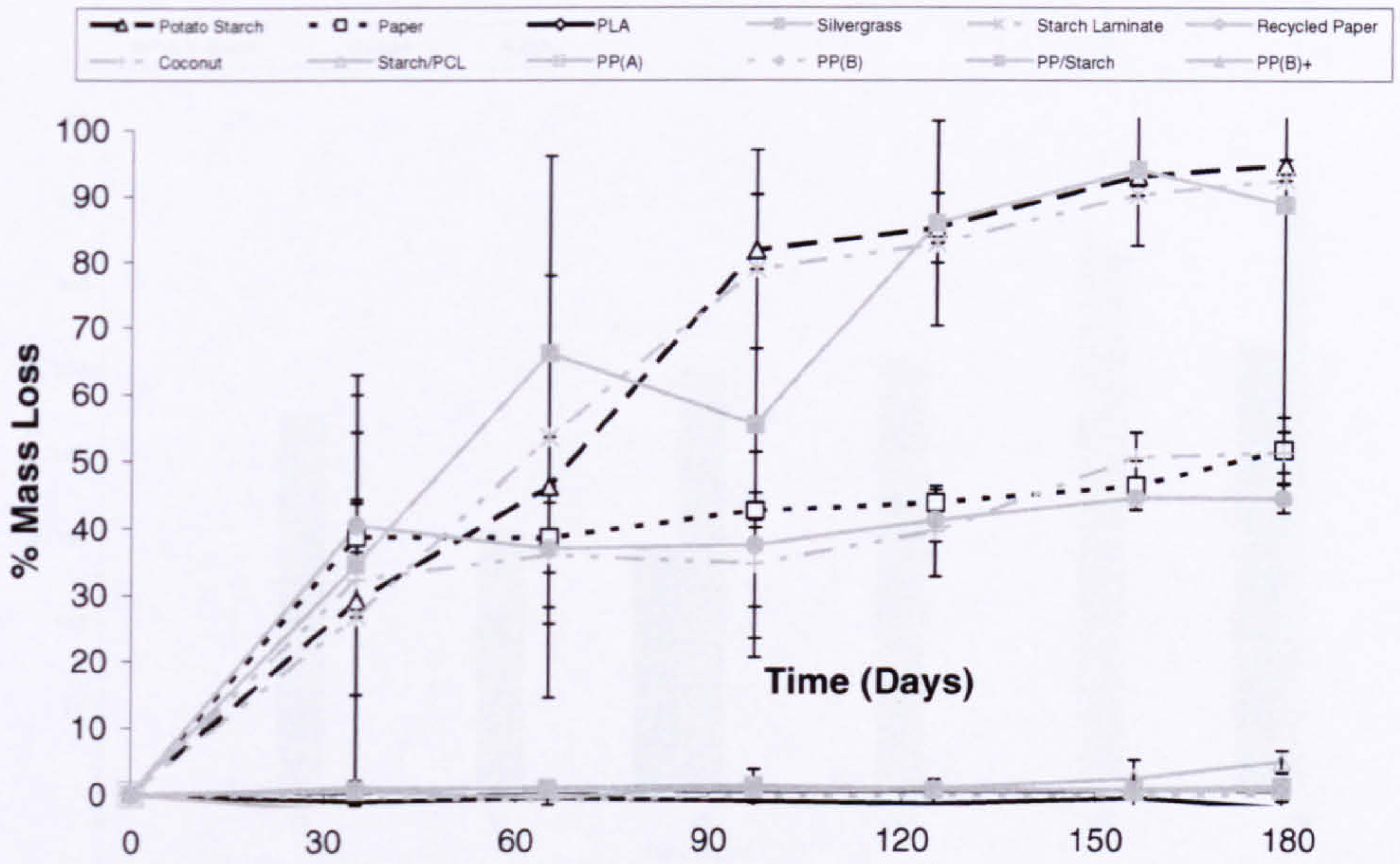

Potato Starch
Paper
PLA
Silvergrass
Starch Laminate
Recycled Paper
Coconut
Starch/PCL
PP(A)
PP(B)
PP/Starch
PP(B)+
% Mass Loss
100
90
80
70
60
50
40
30
20
10
0
Time (Days)
0
30
60
90
120
150
180

Figure 6

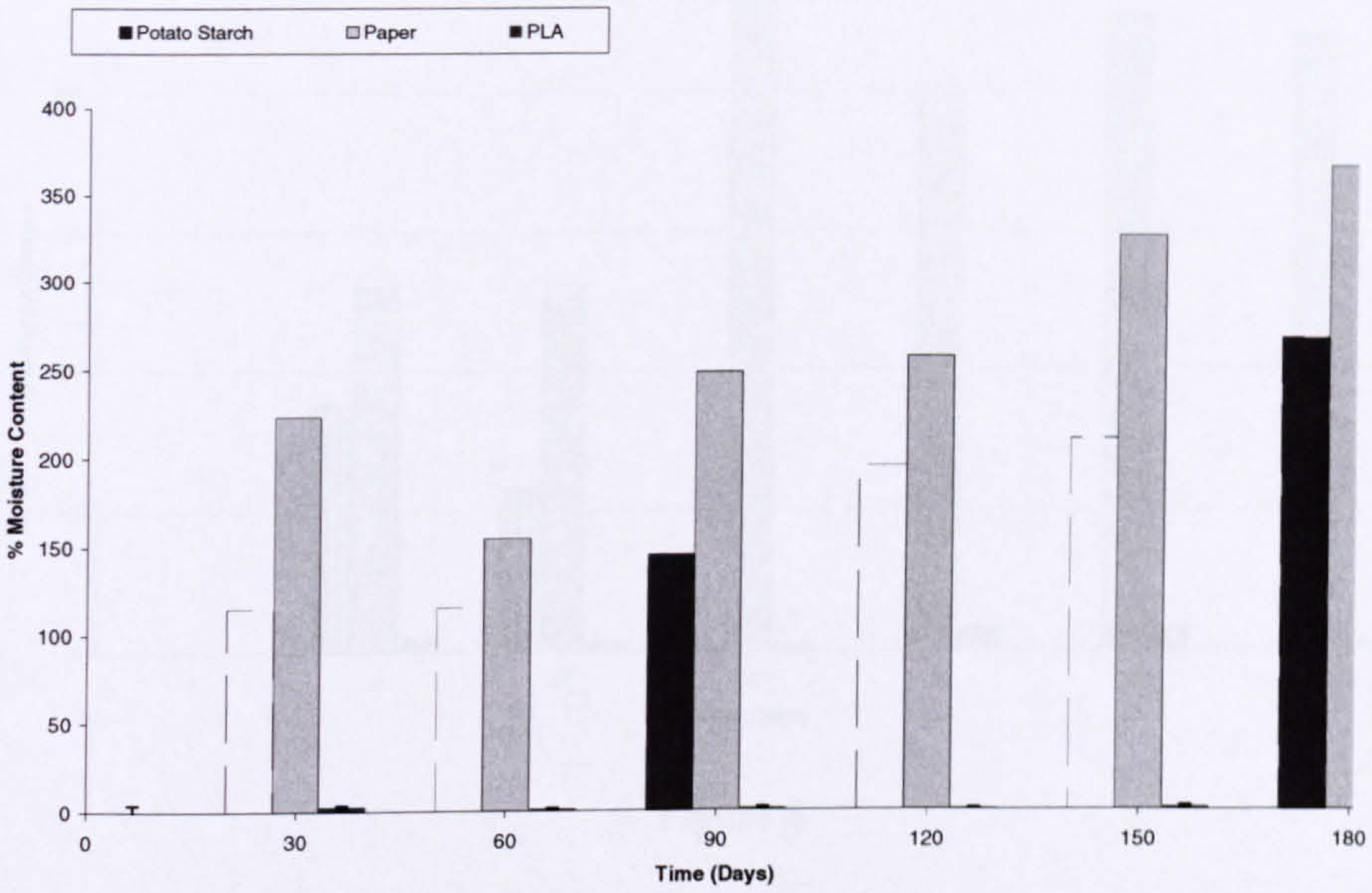

■ Potato Starch
□ Paper
■ PLA
400
350
300
250
200
150
100
50
0
% Moisture Content
0
30
60
90
120
150
180
Time (Days)

Figure 7

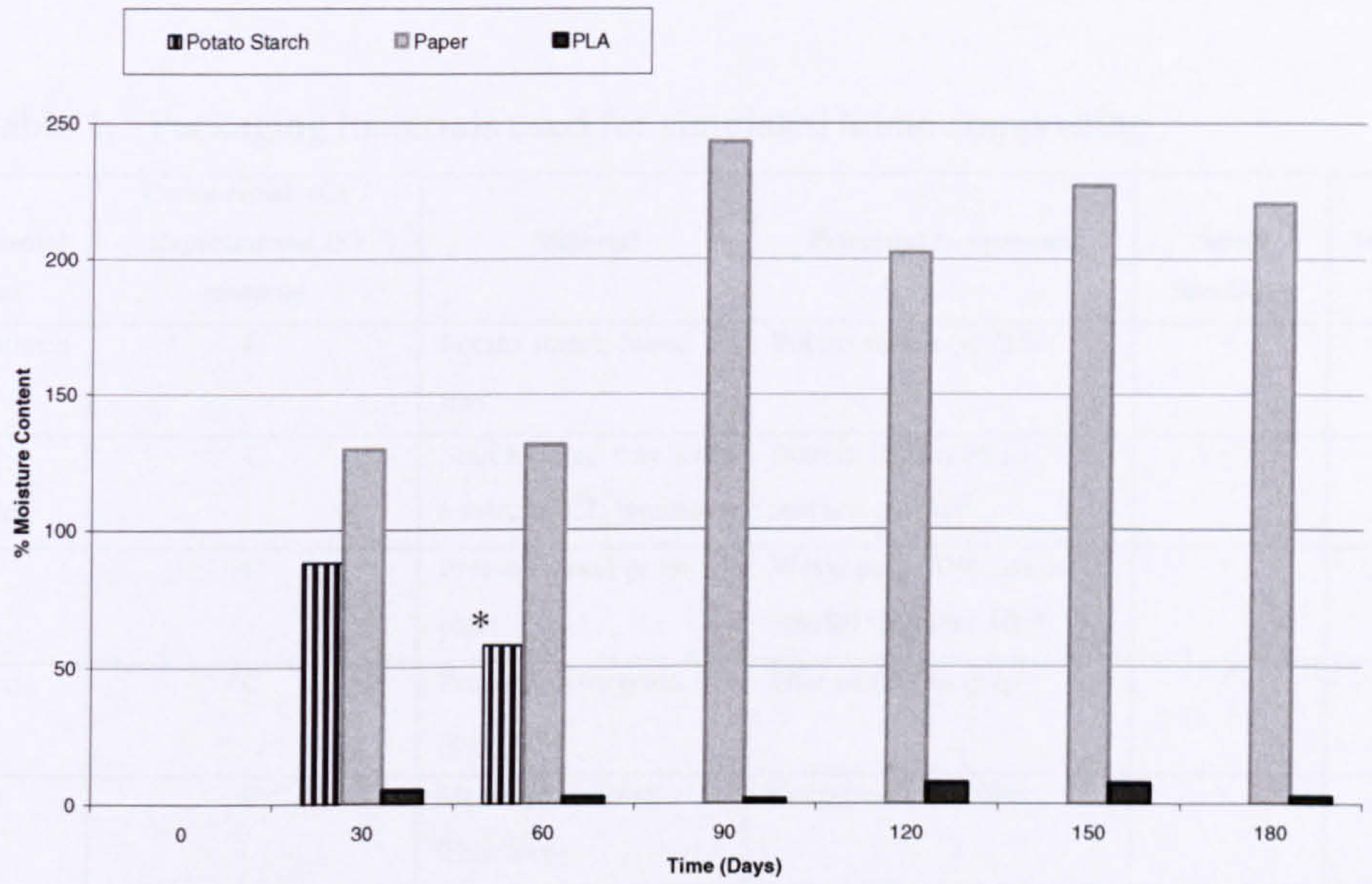


Figure 8

* = mass loss > 80% - no further measurements possible, biodegradation complete

TABLES

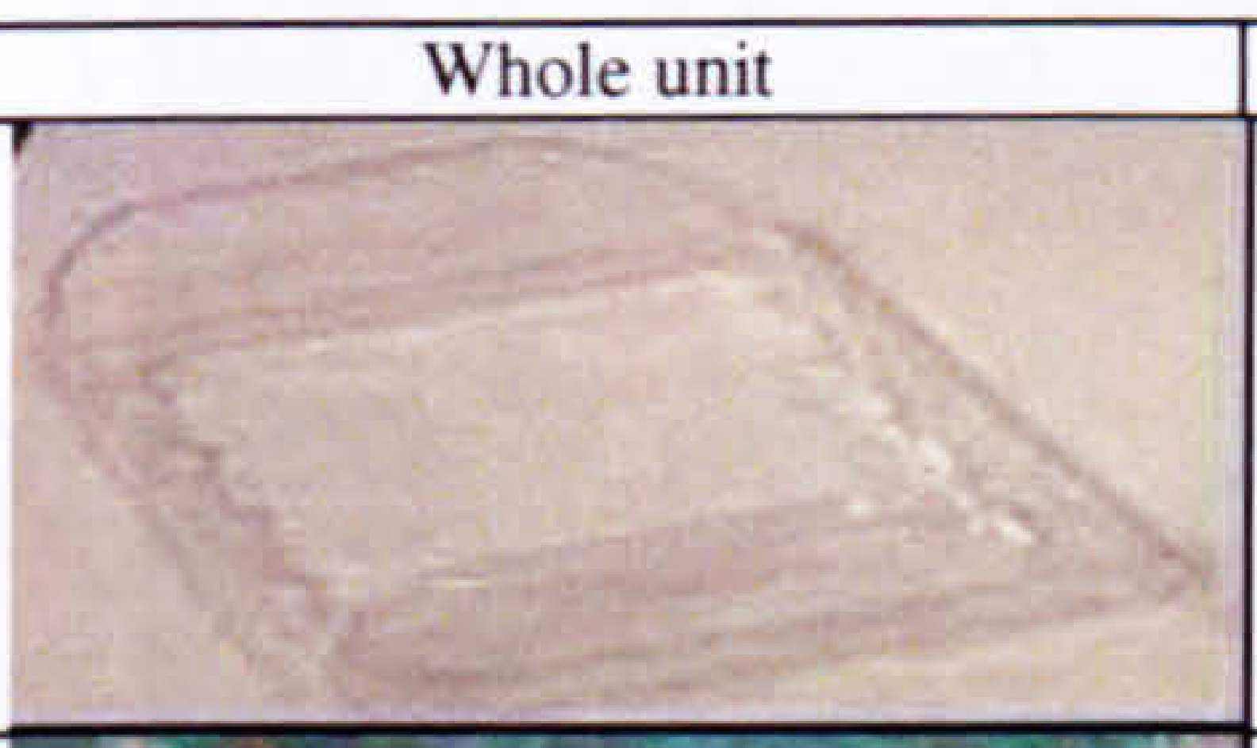
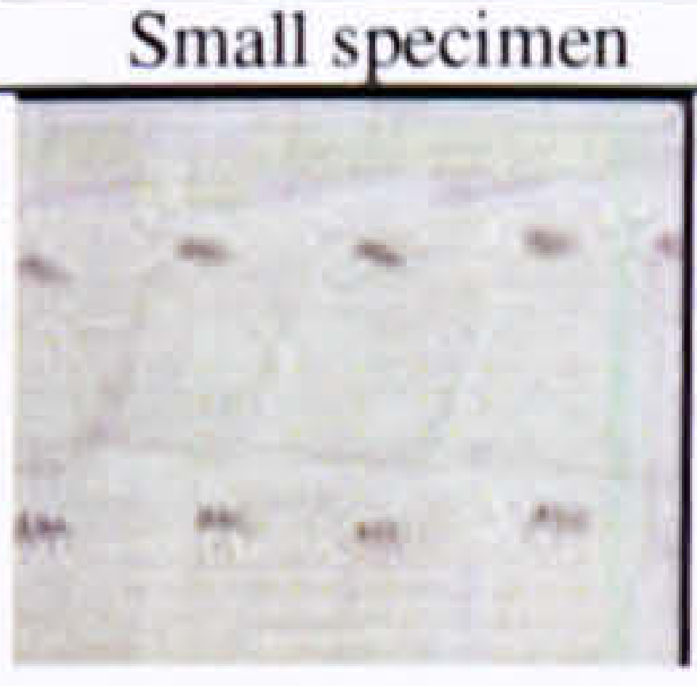
Table 1. Packaging materials used for simulated home composting

Experimental Name	**Commercial (C) / Experimental (E) material**	**Material**	**Principal components**	**Small Specimen**	**Whole unit**	**Rate of Degradation**
Potato Starch	C	Potato starch-based tray	Potato starch (< 75%)	✓	✓	Fast
Starch Laminate	C	Starch based tray with a starch/PCL laminate	Starch; Starch PCL. surface overlay	✓		Fast
Paper	C	Pressed wood pulp plate	Wood pulp 70%: starch size 20 %; other 10 %	✓	✓	Medium
Silvergrass	C	Pressed silvergrass pulp plate	*Miscanthus sp* pulp	✓		Fast
Coconut	C	Moulded coconut fibre tray	*Cocos nucifera* fibre	✓		Medium
Recycled Paper	C	Moulded recycled paper pulp tray	Recycled paper	✓		Medium
PLA	E	PLA tray	100 % PLA	✓	✓	Slow
Starch/PCL	E	Starch/PCL- extrudate sample	100 % Starch/PCL	✓		Slow
PP(A)	E	Polypropylene (PP) with biodegradability additive A	90 % PP; 10% bio-additive A	✓		Slow
PP(B)	E	PP with biodegradability additive B	90 % PP; 10% bio - additive B	✓		Slow
PP(B)+	E	PP with biodegradability additive B plus chalk filler	60 % PP; 10 % bio-additive B; 30 % chalk	✓		Slow
PP/Starch	E	PP compounded with starch granules	88 % PP; Y % 10 starch granules; 2 % other	✓		Slow

All % compositions are on a weight basis

Table 2. Visual assessment of packaging materials during simulated home composting

PLA tray

Day	Whole unit	Description	Small specimen	Description
0		Tray in its original state		Sample in its original state
35		No Degradation observed, trays intact, no mould growth, no free water		No Degradation observed, samples intact, no mould growth, no free water
65		No Degradation observed, trays intact, no mould growth, no free water		No Degradation observed, samples intact, no mould growth, no free water
97		No Degradation observed, but tray shows signs of damage due to manual turning.		No Degradation observed. Samples intact, no mould growth, no free water
124		No Degradation observed, trays intact, no mould growth, no free water		No Degradation observed, samples intact, no mould growth, no free water
156		No Degradation Trays showed signs of breaking up this is due to manual turning rather than degradation		No Degradation observed, samples intact, no mould growth, no free water
190		No Degradation Tray showing some mechanical damage with small fragments missing.		No Degradation observed, samples intact, no mould growth, no free water

Potato starch tray

No. of days in Compost	Whole unit	Description	Small specimen	Description
0		Original tray		Original sample
35		Obvious signs of degradation		Obvious signs of degradation
65		Obvious signs of degradation		Sample has partially degraded.
97		Tray has broken up and it is no longer possible to remove from compost.		Sample has degraded and small remains can be obtained.
124		Tray has broken up and it is no longer possible to remove from compost.		Sample has degraded and small remains can be obtained.
156		Tray has dispersed into tiny fragments, unable to retrieve.		Very small amounts of sample left.
190		Tray has dispersed into tiny fragments, unable to retrieve.		Very small amounts of sample left.

Paper plate

No. of days in Compost	Whole unit	Description	Small specimen	Description
0		Tray in original state.		Sample in original state.
35		Tray shows sign of mould growth and particles adhering themselves to the tray.		Sample shows signs of wetting.
65		Tray very dry and therefore water added to the composting system.		Sample very dry and therefore water added to the composting system.
97		Further signs of degradation and the tray is breaking up.		Further signs of degradation
124		Further signs of degradation and the tray is breaking up.		Further signs of degradation
156		Obvious signs of degradation, tray broken up and bits missing, lots of mould growth.		Obvious signs of degradation, lots of mould growth.
190		Unrecognisable as a tray, very fragile to touch.		Very fragile to touch.

Alternative for Table 2

Property	Material	1	2	3	4	5	6
Moisture	**Starch**	✱✱	✱✱	✱✱✱	✱✱✱✱	✱✱✱✱	✱✱✱✱
	Paper	✱	✱	✱✱	✱✱	✱✱✱	✱✱✱
	PLA	-	-	-	-	-	-
Microbial	**Starch**	✱✱	✱✱✱	✱✱✱	✱✱✱✱	✱✱✱✱	✱✱✱✱
	Paper	✱	✱	✱✱	✱✱	✱✱	✱✱
	PLA	-	-	-	-	-	-
Fragmentation	**Starch**	✱	✱✱	✱✱✱	✱✱✱	✱✱✱	✱✱✱
	Paper	-	✱	✱	✱	✱✱	✱✱
	PLA	-	-	-	-	-	✱
Integration	**Starch**	✱	✱✱	✱✱✱	✱✱✱	✱✱✱	✱✱✱
	Paper	-	-	-	-	✱	✱✱
	PLA	-	-	-	-	-	-

- = property unsuitable for degradation into compost
✱ = property just appropriate for a low level of degradation into compost
✱✱ = property at a good level for degradation into compost
✱✱✱ = *property at a very high* level for degradation into compost – supportive of a maximum degradation rate
✱✱✱✱ = could not be assessed as conversion into compost was complete

Table 3 Moisture content (%, oven dry basis) of small specimens during composting exposure

	Exposure Time (Days)		
Materials	30	90	180
Potato Starch	115.3	145.3	267.1
Paper	223.9	247.8	365.6
PLA	3.0	1.4	2.2
Silver grass	100.7	166.2	325.0
Starch Laminate	80.5	132.2	90.9
Recycled Paper	229.9	196.1	349.1
Coconut	97.7	126.9	337.5
Starch/PCL	1.2	1.7	8.9
PP(A)	1.0	0.5	1.2
PP(B)	0.3	0.0	0.9
PP/Starch	6.9	9.1	11.6
PP(B)+	0.3	0.1	0.7

Table 4 Results of PAS 100 seed germination and seedling development study

Material	Compost Bin	Total No. of weeds per litre of compost	Total fresh mass of seedlings at 28 days	Av. fresh mass of seedlings at 28 days	Total no. of germinated seedlings at 7 days	Total no. of germinated seedlings at 14 days	Total no. of germinated seedlings at 28 days	Germinated seedlings as a % of control seedlings at 14 days	Germinated seedlings as a % of control seedlings at 28 days
		(No/L)	(g)	(g)	(No.)	(No.)	(No.)	(%)	(%)
Starch	Bin 1	36.0	49.9	1.7	29	30	30	120	120
	Bin 2	49.6	47.1	1.7	29	28	28	112	112
Paper	Bin 1	20.5	62.2	2.4	27	26	26	104	104
	Bin 2	56.3	48.6	1.9	26	27	25	108	100
PLA	Bin 1	29.3	38.0	1.4	28	27	28	108	112
	Bin 2	98.7	42.5	1.5	27	28	28	112	112
Control	Bin 1	105.0	45.0	1.6	27	28	28	112	112
	Bin 2	74.4	55.7	2.1	26	27	27	108	108
PRGM Control		1.5	48.1	1.9	25	25	25	100	100