MASTER THESIS

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Examination of Methods for discriminating types of plastic towards low-cost solutions

By: Christoph Vock, BSc

Student Number: 2210297008

Supervisor: FH-Prof. Dipl.-Ing. Dr. Martin Horauer

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Die zunehmende Verbreitung und Vwerwendugn von 3D-Drucktechnologien führt zu einer signifikanten Zunahme von Kunststoffabfällen, deren umweltgerechte Verwertung eine zentrale Herausforderung darstellt. Insbesondere die Sortierung unterschiedlicher Kunststoffarten erweist sich als technisch anspruchsvoll und kostenintensiv. Ziel dieser Arbeit ist die Untersuchung und Evaluierung kosteneffizienter Verfahren zur Trennung und Sortierung von Kunststoffen, um ein ressourcenschonendes Recycling im kleinen Maßstab, insbesondere im Laborumfeld, zu ermöglichen. Im Rahmen der Arbeit wurde ein experimentelles Setup entwickelt, das auf einer Raspberry-Pi-basierten Spektroskopieeinheit, preisgünstigen optischen Sensoren sowie einfachen mechanischen Sortiermechanismen basiert. Die experimentellen Untersuchungen konzentrierten sich auf die Unterscheidung gebräuchlicher 3D-Druckmaterialien wie Polylactid (PLA), Polyethylenterephthalatglykol (PETG), Acrylnitril-Butadien-Styrol (ABS) und Acrylnitril-Styrol-Acrylat (ASA). Die Ergebnisse zeigen, dass insbesondere die Kombination von Nahinfrarotspektroskopie (NIR) und mathematischer Datenanalyse eine zuverlässige Identifikation der Kunststoffe bei geringen Kosten ermöglicht. Die Arbeit leistet damit einen Beitrag zur Entwicklung skalierbarer, nachhaltiger Recyclinglösungen für die additive Fertigung. Abschließend werden Ansätze für eine zukünftige Weiterentwicklung in den Bereichen Automatisierung, verwendung im nicht-Industriellem Umfeld und maschinelles Lernen evaluiert.

Schlagworte: Kunststoffsortierung, 3D-Druck-Recycling, Kosteneffiziente-Spektroskopie, Nahinfrarotspektroskopie

Abstract

Plastic waste from 3D printing poses a growing environmental challenge, particularly due to the difficulty of efficiently sorting and recycling various polymer types. This thesis investigates low-cost methods for discriminating between different kinds of plastics to support small-scale recycling efforts, especially in laboratory environments. Emphasis is placed on evaluating optical sorting, density separation, and spectroscopy-assisted identification techniques. A custom experimental setup was developed, incorporating components such as a Raspberry Pi-based spectroscopy unit, cost-effective optical sensors, and mechanical sorting mechanisms. Experimental analysis focused on differentiating common 3d-printing materials like Polylactic Acid (PLA), Polyethylene Terephthalate Glycol (PETG), Acrylonitrile Butadiene Styrene (ABS), and Acrylonitrile Styrene Acrylate (ASA). Near-Infrared Near Infrared Spectroscopy (NIRS), combined with mathematical data processing, demonstrated promising results in achieving accurate plastic identification at minimal cost. The findings highlight the potential for scalable, low-cost recycling solutions and contribute to sustainable practices in additive manufacturing environments. Recommendations for future research include further small scale solutions, automation, and the application of machine learning algorithms for enhanced sorting accuracy.

Keywords: Plastic Sorting, 3D Printing Recycling, Low-Cost Spectroscopy, Near-Infrared Sorting

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Contents

1 Introduction

3D-printing technology is constantly developed and increasingly integrated into different kinds of manufacturing and fabrication processes, even in industrial applications. Combined with the demand for renewable and environmentally friendly manufacturing solutions, quick and reliable recycling methods reduce the waste of plastics that are already produced. Contrary to the approach of developing new materials from renewable sources altogether. To ensure that the recycled materials are produced to a certain standard, the sorting process has to meet specific reliability criteria, which poses a big challenge. Another important factor is efficiency, especially in industrial waste processing, where large amounts of plastic waste are handled in a certain amount of time, so the sorting process has to be able to keep up with these rates. This project aims to combine both aspects, reliability and speed and to investigate a low-cost method of visual discrimination of different kinds of plastics.

1.1 The role of plastics in our society

To understand the relevance and impact of this thesis and the field of recycling technologies as a whole, it is important to look back at how plastic became so popular. Plastics have become essential for modern industries, but their story starts way earlier. The first synthetic plastic, Bakelite, was invented by Leo Baekeland in 1907. It was a huge step forward due to its characteristics, being easily moldable and durable at the same time. Plastics gained popularity after World War II as they replaced traditional materials, for example in packaging, electronics and automotive industries. Today, plastic is used in all sectors of industry due to its versatility and cost-effectiveness [1]. Plastics have a broad range of properties and, therefore, different cases. Common plastics include Polyethylene Terephthalate (PET), High Density Polyethylene (HDPE), Low Density Polyethylene (LDPE),Polypropylene (PP), Polystyrene (PS), and Polyvinyl Chloride (PVC). Even though these materials differ quite a bit in density, strength, flexibility, etc., manual differentiation remains very difficult. This complicates the recycling process excessively, as conventional recycling methods struggle to identify and sort different types of plastic efficiently.

1.2 Environmental challenges

In the last 65 years, the production of plastics has increased by more than 18,000.00% from 2 million metric tons in 1950 to 380 million metric tons in 2015. Two-thirds of this material ends up back in our ecosystem. Microplastics are the result of plastic material not decomposing, but rather breaking down into smaller particles. This form of plastic can easily and undetected spread into all ecosystems. Traces can be detected in our soil, and groundwater and a study from 2022 has shown that microplastics can even be found in human lungs and blood [2]. In some cities like Vienna, a central part of the waste is incinerated to create energy or heat. This is a way to reuse waste and turn it into a helpful resource without the need for sorting plants.

1.2.1 Motivation

Waste separation and recycling are essential steps in reducing environmental pollution and conserving resources. However, these systems often rely on large-scale infrastructure, expensive equipment, and high levels of automation. For smaller applications or individual users, these solutions are often not practical or accessible.
3D printing is becoming more and more integrated into modern manufacturing processes. While it offers flexibility and speed, it inevitably leads to plastic waste that is not negligible. Especially in smaller labs or workshops, leftover filament, failed prints, and support structures accumulate quickly. Unlike large-scale industrial settings, these environments often lack the resources or infrastructure to sort and recycle plastic waste properly. Current solutions are usually expensive, over-engineered, or focused on large-scale operations. This creates a gap where low-cost, small-scale systems could be the answer to bring recycling solutions to these minor operations. The motivation behind this thesis is to evaluate existing sorting and recycling methods that are utilised on an industrial scale and see which ones can be adapted for such an environment. By combining low-cost components with proven techniques, this work aims to offer a realistic path towards better plastic reuse, especially for 3D printing waste.

2 Recycling of Plastics: From History to Future Perspectives

Plastics have revolutionised the world in many ways. Nearly all products are packaged in plastic due to its appealing look and low production cost. Plastic is also straightforward to process and shape in every required way. One of the most significant contributors is usually quoted as the automobile industry. Before plastic was readily available, many parts were made from metal or real wood. These materials are expensive in their acquisition and require skilled workers to process them. However, their widespread use has created a significant environmental problem. Due to their non-biodegradability and the challenges associated with their recycling, environmentally aware groups have condemned plastic use. Recycling plastic has become essential to reduce pollution and conserve resources. By developing new ways to reuse plastic waste effectively and designing new biodegradable materials, pollution can be reduced. This chapter explores the history of plastic recycling, current state-of-the-art methods, and the future of recycling technologies, focusing on sorting and new approaches to plastic management.

2.1 Evolution of Plastic Materials

The history of plastic materials dates back to the mid-19th century, when the first synthetic polymer, Bakelite, was invented in 1907 by Leo Baekeland. However, plastic as we know it today gained popularity during the mid-20th century, particularly after World War II. The development of Polyethylene (PE), PVC, and PP led to a surge in plastic production due to their versatility, durability, and low cost. By the 1960s, plastics had penetrated almost every industry, from packaging to construction.

This rapid expansion of plastic use came with a corresponding increase in plastic waste, leading to concerns about environmental pollution. Early efforts to address this issue focused on landfill disposal, as plastics' durability and resistance to degradation posed significant waste management challenges. However, with growing awareness of the environmental impacts, particularly the persistence of plastics in landfills and oceans, recycling became a priority in the 1970s.

2.1.1 Early Recycling Initiatives

Local governments and environmental organisations largely drove the earliest recycling initiatives. In the 1970s and 1980s, curbside recycling programs began to appear in major cities across the United

States and Europe, with plastics being one of the primary materials collected. However, these early programs faced several challenges. Plastics are made from a wide range of polymers, and different types cannot be easily mixed during recycling without compromising the quality of the recycled material. This issue of polymer compatibility meant that most recycled plastic was downcycled into lower-quality products, such as park benches or plastic lumber.

Despite these challenges, early recycling programs laid the groundwork for more advanced techniques and systems that would emerge in the coming decades. The introduction of the Resin Identification Code (RIC) system in 1988, which categorises plastics by type (e.g., PET, HDPE, etc.), was a crucial step towards improving the sorting and recycling process. However, the overall recycling rates for plastics remained low throughout the late 20th century, as most waste continued to be incinerated or landfilled.

2.1.2 Technological Advancements in Plastic Recycling

Technological advances in the 1990s and early 2000s significantly improved plastic recycling. Mechanical recycling processes, which involved shredding and melting plastic waste into pellets for reuse, became more efficient, though they still suffered contamination and polymer degradation limitations. At the same time, chemical recycling technologies, which break down polymers into their monomers, began to be developed. These processes, including depolymerisation and pyrolysis, offered the potential to recycle plastics that are difficult or impossible to process mechanically, such as multilayer packaging and mixed polymer streams.

However, chemical recycling remained expensive and energy-intensive, limiting its widespread adoption. By the early twentieth century, most plastic recycling still relied on mechanical methods, with recycling rates varying significantly by region and polymer type.

2.2 State-of-the-Art Plastic Recycling Techniques

Mechanical recycling is the most widely used method for the processing of plastic waste. The process typically involves collecting, sorting, washing, shredding, and melting plastic waste into new pellets that can be used to manufacture new products. Although mechanical recycling is straightforward and can be applied to various thermoplastics, it has several limitations. One major challenge is the degradation of plastic polymers during each cycle, which reduces the material's physical properties, such as strength and flexibility. This means that plastics can usually only be recycled a limited number of times before they become unusable.

Another significant challenge with mechanical recycling is contamination. Contaminants such as food residues, labels, and non-compatible plastics can impair the quality of the recycled material. This requires a thorough cleaning and sorting of the waste, which can be labour-intensive and energy-intensive. Innovations in automated sorting technologies, such as Near Infrared (NIR) sensors, have improved the efficiency of this process, but contamination remains a significant barrier to increasing recycling rates.

Chemical recycling represents a more advanced approach to plastic waste management. Instead of physically reprocessing the waste, chemical recycling breaks down plastic polymers into their basic building blocks, or monomers, which can then be purified and re-polymerised into new plastics. There are several different methods of chemical recycling, including depolymerisation, pyrolysis, and gasification.

- **Depolymerisation** involves breaking down polymers back into their monomers using chemical reactions such as hydrolysis or solvolysis. This method is particularly promising for recycling certain plastics, such as PET and polyamides, which can be depolymerised relatively easily and re-polymerised into high-quality materials.
- **Pyrolysis** involves heating plastic waste in the absence of oxygen to break it down into smaller molecules, typically producing a mixture of liquid hydrocarbons (pyrolysis oil), gas, and char. The pyrolysis oil can be refined into new chemicals or fuels, while the gas and char can be used for energy generation. Pyrolysis is suitable for a wide range of plastic waste, including mixed and contaminated streams that are difficult to recycle mechanically.
- **Gasification** is a related process that converts plastic waste into a mixture of carbon monoxide and hydrogen, known as syngas, which can be used to produce chemicals or energy. Gasification is more energy-intensive than pyrolysis but offers greater flexibility in the types of waste that can be processed.

Chemical recycling has the potential to address many of mechanical recycling's limitations, such as polymer degradation and contamination. However, it is still in the early stages of commercialisation and faces significant challenges related to cost, scalability, and environmental impacts.

2.2.1 Plastic Incineration and Energy Recovery

Plastic incineration is another method used for managing plastic waste, particularly in regions where recycling infrastructure is underdeveloped or where the waste is too contaminated to be recycled. Incineration involves burning plastic waste in controlled conditions to generate heat, which can be used to produce electricity or steam for industrial processes. While incineration can reduce the volume of plastic waste by up to 90%, it also produces Greenhouse Gases (GHGS) and other pollutants, such as dioxins and furans, which require careful management.

Modern Waste to Energy (WTE) plants are designed to minimise emissions and maximise energy recovery, but the environmental impacts of incineration remain a contentious issue. Many environmental organisations argue that incineration discourages recycling and contributes to climate change. Nonetheless, incineration plays a significant role in plastic waste management, particularly in countries with limited landfill space.

2.3 Future Directions in Plastic Recycling and Sorting

The success of any recycling program hinges on the ability to sort different types of plastics efficiently. Traditional sorting methods, such as manual separation and density-based sorting, have proven insufficient to cope with the growing complexity of plastic waste streams. Recent advancements in sorting technologies, particularly optical and robotic systems, are helping to overcome these challenges.

Optical sorting technologies, such as NIR spectroscopy, can identify different types of plastics based on their spectral signatures, allowing for high-speed and accurate separation of polymers. Robotic systems equipped with Artificial Intelligence (AI) and machine learning algorithms are also being developed to enhance sorting capabilities. These robots can quickly identify and sort plastics based on their colour, shape, and polymer type, improving the overall efficiency of the recycling process.

2.3.1 Biodegradable and Bio-based Plastics

The development of biodegradable and bio-based plastics offers another potential solution to the plastic waste problem. Biodegradable plastics are designed to break down in natural environments or industrial composting facilities, reducing the amount of plastic waste that ends up in landfills or oceans. However, the widespread adoption of biodegradable plastics faces several challenges. For instance, many biodegradable plastics require specific conditions, such as high temperatures or moisture, to decompose, making it challenging to ensure that they will degrade properly in the environment.

Bio-based plastics, made from renewable resources such as corn starch or sugarcane, also offer environmental benefits by reducing reliance on fossil fuels. However, bio-based plastics are not necessarily biodegradable, and their ecological impacts depend on factors such as land use, water consumption, and the lifecycle of the products they are used to create.

2.3.2 Closing the Loop: Towards a Circular Economy

Plastic recycling aims to create a circular economy in which materials are continuously reused and recycled, reducing the need for virgin plastic production and minimising waste. Achieving this goal will require a combination of technological innovation, policy support, and changes in consumer behaviour.

Extended Producer Responsibility (EPR) schemes, in which manufacturers are held accountable for the lifecycle of their products, can incentivise the design of more easily recyclable plastics and reduce the environmental impact of plastic production. At the same time, investments in new recycling technologies and infrastructure will be essential to improving recycling rates and reducing the ecological footprint of plastics.

In the long term, developing advanced chemical recycling methods, biodegradable plastics, and AI-driven sorting technologies could enable a fully circular plastic economy where waste is minimised and resources are conserved.

2.3.3 The role of Human Labour in Recycling

Human workers have traditionally carried out waste sorting. Manual separation is still widely used in many parts of the world, particularly in facilities with limited access to automation technology. Workers are typically stationed along conveyor belts, where they are required to identify and pick out specific types of waste based on material, shape, or colour. This process is repeated continuously over long shifts and under time pressure.

Although manual sorting can be quite accurate, especially when dealing with materials that are difficult to classify using machines, it comes at a cost. Physically, the work is highly demanding. It often involves repetitive motion, standing for long periods, and exposure to dust, noise, and potentially hazardous materials. Over time, this can lead to serious health issues, including musculoskeletal problems, respiratory conditions, and high levels of fatigue. In addition, the repetitive and monotonous nature of the work can cause psychological stress.

As recycling volumes grow and material types become more complex, the need for ergonomic improvements and automation becomes more critical. Reducing the dependence on human labour not only improves worker safety and well-being but also increases consistency, efficiency, and overall system resilience.

2.3.4 Research Questions / Hypotheses

Research Questions:

- Which existing plastic sorting methods are most suitable for adaptation to low-cost laboratory environments?
- Can commonly used 3D printing materials be reliably identified using accessible technologies like NIR spectroscopy?

Hypotheses:

- It is possible to adapt at least one industrial sorting method to work reliably in a low-cost, small-scale environment.
- Near-Infrared spectroscopy can distinguish between selected 3D printing polymers with a high degree of accuracy, even using basic hardware.
- The main limiting factors for small-scale plastic sorting are not the detection methods themselves, but the environmental variability and mechanical handling.

2.3.5 Objectives of the Research

This thesis aims to examine different aspects of the plastic recycling process to create a complete system for reusing 3D-printer waste in a laboratory setting. First, all parts of such a system will be identified and examined for characteristics pertaining to its use in a small-scale, low-cost laboratory environment. Figuring out which systems can be sensibly used in such an environment will lead to a complete waste recovery system blueprint.

2.3.6 Methodology Overview

This thesis follows a structured approach to evaluate industrial waste recycling technologies, focusing on their suitability for small-scale reproduction. First, a broad survey of standard industrial plastic waste recycling methods was conducted, including mechanical, optical, thermal, and chemical techniques. Each method was assessed based on scalability, technical complexity, equipment availability, and feasibility of implementation in a laboratory or pilot-scale setting. Based on this evaluation, three methods were selected for further investigation: optical sorting, density-based separation, and spectroscopy-assisted identification. These methods were chosen due to their relevance in modern recycling processes and their potential for being modelled and tested under controlled, small-scale conditions. The following sections describe each method in detail, including its operating principles, typical industrial implementations, and adaptations for experimental analysis.

2.3.7 Scope and Limitations

The central aim of this thesis is to explore whether low-cost and small-scale systems can reliably separate different types of plastic, with a particular focus on waste generated by 3D printing processes.

3 Separation Principles and Classification Criteria

To create a baseline for a waste recycling system, the first step is to identify all criteria by which waste can be sorted. Following this step, the requirements will be evaluated to determine if they pertain to the 3D-printing use case. Since this thesis only concerns itself with plastic waste, the criterion of the state of matter can be disregarded. Only solid waste will be the focus of this chapter.

3.1 Separation by Particle Size

The first step in almost all Material Recovery Facility (MRF) plants is the separation by size [3]. To ensure safety for all MRF equipment down the line, this step ensures that small particles like tiny rocks or small food particles are expelled from the process right away.

To ensure that no glass particles make it through this stage, it is common to mechanically break down the waste via hammers, heavy rollers, or similar machines. Since glass is often found in larger chunks, it will be crushed, and the small particles will sieve out. Polymers or other more flexible particles will not be affected. All waste particles are then sifted by large trommel screens or similar equipment.

3.1.1 Application for 3D-printing waste

3D-printing waste comes in 3 major forms.

- **Printing Support:** Some printing technologies cannot print horizontal unsupported volumes. Therefore, the software that calculates the printing path for a given model will add support structures to the print. These act like scaffolding for the overhanging portion of a print. The support is usually lightweight to reduce wasted material and is designed to be removed easily after printing.
- **Missprints:** 3D printers have made great strides in their effort to be more user-friendly. Nevertheless, they still require extensive knowledge of printing techniques, materials, and mechanics to set up and carry out a print correctly. This does not automatically mean that a print will be successful. Since most prints of average size usually take a few hours to finish, watching over a print from start to finish would not be feasible. Missprints can lead to Blobs, which are

huge filament deposits in one solid, melted shape, or to stringing. Stringing happens when the printer extrudes material but is in the wrong location, so the material spills out of the nozzle and accumulates in a twisted mess of strings [4].

- **Leftover Filament:** The material used for Fused Deposition Modeling (FDM) 3D printing comes in spools of filament and is measured by weight. For consumer purposes, the average size of a spool is 1000g. If less than the required amount for a print is left on the spool, another spool must be used. Some technologies allow for the fusion of two lengths of filament. Although not expensive, these methods are usually quite time-consuming and require some practice to achieve reliable results. For short lengths, this is generally not feasible, so they are also disregarded.

Because the expected size of waste is quite different, the sorting does not require an automated setup. The various kinds of waste can be easily separated and processed individually. Since recycling usually involves grinding down the waste into small particles, the size does not come into effect after this point. For bigger facilities, a grinder that can manage all three kinds of waste without prior sorting would simplify the procedure even more.

3.2 Separation by Colour

Sorting waste by colour is historically done by human labor, even on an industrial level. This fact has motivated different companies to develop automated sensor-based solutions to increase efficiency and to increase the recovery rate of recyclable materials [5].

3.2.1 Principal

The traditional system of sorting waste by colour consists of huge conveyor belts run by human labourers. The workers pick through the waste and sort it by a specific colour characteristic. To ensure an accurate result, multiple people have to work on the same waste stream. This work constantly stresses the body, and the repetitive work leads to increased psychological stress in the workforce. Safety concerns are also ever-increasing. Humans are usually limited to about 40 picks per minute, the unit used to measure efficiency in waste sorting. Robotic sorting solves these and other problems and brings further improvements.

- **Working Time Restrictions:** Automated sorting stations operate 24/7 with minimal downtime. This operation leads to increased productivity. The estimated downtime for such systems is less than 1%.
- **Continuous Accuracy:** human pick rates are way inferior to automated systems and are also not continuous throughout the workday. Human labour tends to decline due to fatigue and other environmental changes. Automated systems remain at a steady, high-capacity peak rate.

- **Cost:** As in any industry, the cost of a service is the driving factor for development. MRFs that implement automated systems experience an average 70% reduction in labor costs and a 100% increase in productivity.
- **Resilience:** Robots are engineered to endure environments that are unsuitable for human workforces. Labor laws stipulate strict conditions to ensure the health of workers. Autonomous systems, on the other hand, are designed to withstand temperatures ranging from 0 ℃ to 40 ℃, which can be typically found in MRFs.
- **Quality Control:** Automatic sorting systems rely on software that easily supports 24/7 monitoring. AI models used for training and controlling sorting performance can be adapted at any time and from anywhere. Human work quality can only be controlled retrospectively and declines over time due to fatigue.
- **Installation & Maintenance:** Provided that all necessary infrastructure is provided, the commissioning and maintenance of these systems are straightforward. The only real maintenance needed is continuously replacing worn-out parts, like grabbing arms or suction cups for picking.

3.2.2 Application for 3D-printing waste

This process is crucial as 3D printing usually relies on the purity of colour. In a technical environment, 3D printing is generally done with simple colours like black, grey, or white. More extraordinary colours are available but are usually not used. Therefore, the true pureness of colour is actually of lesser significance. The real benefit of optical sorting lies in spectroscopy. This way, plastics can be sorted not only by colour but also by specific material. This is the key to accurate material sorting since, to the human eye and standard photonic sensors, materials can look optically the same but be comprised of different polymers. This approach will be further explored in the practical part of this master's thesis.

3.3 Separation by Density

Density-based separation is also a widespread approach in MRFs. The idea is to use methods to separate materials like plastics and others based on their specific weight. The process is economical, scalable, and compatible with other wet or dry processes [6]. Different approaches are used throughout industrial MRF plants around the world.

3.3.1 Sink-Float Separation

The simplest density-based sorting method is the sink-float separation process. In this method, shredded plastic particles are mixed with a liquid medium. This medium is usually water-based and mixed with additives to alter the density. Plastics with a density lower than the liquid (e.g., PE and PP) will float, while denser plastics (e.g., PVC, PET) will sink [7].

The density of plastics commonly found in waste sorting plants:

- **PE:** 0.91–0.94 g/cm^3
- **PP:** 0.90–0.92 g/cm^3
- **PS:** 1.04–1.06 g/cm^3
- **PVC:** 1.30–1.45 g/cm^3
- **PET:** 1.38–1.41 g/cm^3

3.3.2 Hydrocyclone Separation

A more precise method for separating by density is a hydrocyclone system. These utilise centrifugal forces in a cone-shaped chamber to separate particles based on minimal differences in density. This process can sort similar plastics and is often used to separate PET from PVC, which can be very similar in terms of density [8].

3.3.3 Challenges and Considerations

Density-based sorting is widely used but comes with some drawbacks. If plastics are dirty or impure, they can alter their density and lead to mislabeling. Furthermore, materials made up of different compounds or layered plastics cannot be separated using this method alone [9]. Additional sorting systems, such as NIR spectroscopy or electrostatic separation, are typically used in combination to ensure a reliable and accurate sorting outcome.

3.3.4 Application for 3D-printing waste

Density-based separation offers limited but targeted usability in the context of 3D printing waste. Since most FDM printers rely heavily on just a few kinds of polymers, such as PLA, PETG, and ABS, density-based separation can be implemented [7]. However, the biggest downside lies in the material used itself. Because the plastics used in 3D printing are all processed the same, i.e. remelting through a nozzle, they are usually very close in density. Other factors like additives for enhanced properties like colour or strength can vary the density, leading to misclassification [8]. For example, PLA and PETG can sometimes only be reliably separated using salt solutions with fine-tuned densities, which makes the process more involved and sensitive to impurities [10]. Density-based separation is not feasible in smaller-scale environments, such as small labs or workshops. For industrial settings, however, where large quantities of sorted waste accumulate, a sink-float system is used as a helpful reprocessing step. The most significant advantage is that any optical sorting method can not process density, whether human labour or sensor-based [9].

3.4 Separation by Magnetic Behaviour

Sorting materials based on their magnetic behaviour is one of the simplest yet effective processes to sort waste. Ferrous metals or mixtures of materials that show ferrous behaviour are desirable to extract from waste mixtures as they are valuable compared to other materials.

The setup of these systems is quite basic: a static magnet or a magnetic field run by a stream of waste. All particles that are attracted to the magnetic field will be picked up. Subsequently, the magnetic waste will be removed from the magnet either mechanically or by altering the attraction forces of the magnet, i.e., turning off electromagnets. There are only three ferrous metals: iron, nickel, and copper. Copper is the most valuable metal, so all pieces containing any of these metals can be sifted out. Magnetic sifting can also be combined with other methods and is usually done at the beginning of the sorting process.

3.4.1 Application for 3D-printing waste

Initially, the idea of using magnets to sort 3D printable materials was quickly disregarded, but there are numerous applications where metal-containing materials are valuable.

- **Functional Prototypes with Enhanced Properties:** Thermal conductivity, stiffness, and abrasion resistance are not usually compared to standard filaments like PLA. Therefore, these material combinations create the ideal base for certain application prototypes [11].
- **Electromagnetic Interference (EMI) Shielding:** EMI has significant implications in the field of embedded systems. Stainless steel and carbon-filled filaments have been successfully implemented in EMI shielding and even conductivity components [12].
- **Casting Applications via the Lost PLA Method:** In a more mechanical sense, Bronze- or copper-filled PLA is often used to produce blanks for casting applications where a pure metal product is needed. The printed models are heated until the soft polymer combusts in a kiln, leaving the pure metal structure behind. This process can create very precise models [13].

One of the significant downsides of these materials is the excessive wear they put on the 3D printer. Metal particles pushed through the extruder can literally grind out the nozzle. Like an abrasive paste, the nozzle hole can be widened since it is typically made of soft brass. This grinding can lead to inaccuracies, especially if the user is unaware of the metallic content.

3.5 Separation by Electrostatic/Triboelectric Behaviour

To successfully reintroduce a recycled material into the production stream, one of the biggest challenges comes in the form of composite materials. Only pure and non-contaminated plastics can be successfully reused. Mechanical sorting systems are often limited in their use because the materials are presented in a mix of different waste streams. Optical or density-based processes are challenged by a mix of similar materials in density, colour, and mechanical behaviour. Therefore, these systems loose economic efficiency in managing these tasks [14].

Two main techniques are used to exploit the electrostatic charge of particles in waste sorting. The first step in all electrostatic sorting systems is charging the materials. There are a few different ways to achieve this:

- **Triboelectric Charging:** Most systems take advantage of the triboelectric effect. The mixture of particles is brought together and is mechanically agitated. Through this physical friction, electrons are exchanged between the particles based on their dielectric constant. The dielectric constant describes how well a material stores electrical energy. Based on this constant, materials are either more likely to give away electrons or take up free electrons from other materials. Through this process, the materials acquire different charges, allowing them to be separated accordingly.
- **Corona Discharge (Ion Bombardment):** Another very popular method is the Corona discharge method. A sharp, pointed electrode is placed near waste particles. The electrode is then charged with a high voltage in the range of 30-1100kV [15]. After the voltage reaches a critical value, the electrode discharges continuously, releasing ions. These ions interact with the material surface, and depending on the electrode's charge, they transfer said charge to the objects.
- **Induction Charging:** Different to triboelectric charging, induction charging works contactless. The waste stream is exposed to an electric field, which will cause insulating materials like metals to take on the charge of the field. Insulating materials like plastics are not affected and stay neutral in their charge state.
- **Thermoelectric Charging:** When materials with different thermoelectric properties experience a large gradient in temperature, their state of charge changes. The burst of heat promotes the flow of electrons in certain materials [16]. Thermoelectric charging is weaker and much harder to control than other methods due to the variations in thermal conductivity caused by surface contact.
- **Photoelectric Charging:** When Ultraviolet (UV) light or other high-energy light sources strike a material, it causes the freeing of electrons, causing the material to take on a positive charge. Again, conductive materials are more responsive to this charge than isolators. [17].

Drum Type Seperator

The most common type of electrostatic separation system is the "drum type". After the particles are charged, they are fed onto a large rotating drum. The drum is charged with an electric charge or, in some cases, grounded. The particles are moved through an electric field opposite to the drum. Particles that are attracted to the drum will stay stuck to the drum until they are eventually mechanically brushed off at the bottom of the drum. Other particles are either attracted to the opposing electric fields and pulled off the drum or are not attracted to either field and are flung off the drum by their momentum. Brushed off particles are separately collected from the other particles.

Free-Fall Type Seperator

A free-fall separator works with a similar principle, except that the particles are dropped into a chamber that is exposed to a high-voltage electric charge. Similarly to the drum-type systems, neutral or weakly charged particles conform to the regular physical forces, which leads them to fall mostly straight down. Charged or conductive particles are attracted to one of the sides and alter their trajectory accordingly [18].

3.5.1 Application for 3D-printing waste

Electrostatic separation can be helpful in the context of 3D printing waste. As long as the characteristics of each polymer are known, the system can be adapted accordingly. Since this process is exclusively performed on granulated materials, otherwise it would lead to an impression, it fits perfectly into the workflow of 3D printing recycling. Granulation and shredding of plastic waste is a significant step in all 3D printing waste recycling and plastic recycling in general. The only aspect that requires a lot of attention is the control of the immediate environment. Heat, moisture or contaminants will render this process very imprecise and lead to impure results.
To adapt systems that are used in the industry today to the environment of small-scale 3D printing labs, all processes must be examined. Subsequently, some promising ideas are discussed and developed further in the following chapters, and additionally, 3D printing is also set in the context of Embedded Systems Automation. These systems have the potential to be utilised in small-scale, low-cost operations.

4 Optical sorting

Historically, optical sorting systems were powered by human labour. This chapter will examine the challenges associated with finding automated solutions and how these solutions can be applied to a low-cost alternative environment.

4.1 Basics of Automated Optical Sorting

Optical sorting solely relies on visual cues to sort through waste streams. The first optical sorting systems were created for agriculture applications around 1930 and could only differentiate between two colours. Since then, optical sensors and computational power have increased exponentially.

4.1.1 Components of Optical Sorting

The most basic concept of an Optical sorting system is comprised of three parts, as seen in figure 4.1. Here is a short overview:

- **Conveyor:** A conveyor belt is the simplest form of moving a waste stream along. This piece of equipment needs enough space to transport all of the waste in a single-layered manner. If pieces overlay too much, the optics will not detect them correctly.
- **Optics:** Optics can range from standard cameras to UV or Infrared (IR) sensors. The selection of the optic is based on the specific application. Different choices can be combined to create more reliable and flexible systems. The appropriate lighting, in combination with the sensors, is also a critical factor. Since optic sensors are extremely sensitive, the light source must create the correct brightness and light colour and be flicker-free.
- **Sorter:** After the optic sensor has detected a piece of material that needs to be sorted, a mechanical system needs to pick it out of the stream. This system has to be quick and precise to ensure an appropriate throughput of material. To ensure this quickness, sorting systems are usually kept mechanically very simple. The most common type is the air pressure sorting for materials that are light enough. A jet stream of air is pointed at a piece of waste and is consequently blown off the waste stream.
- **Controller:** The controller analyses the data stream from the optical sensors, decides which sorting action has to be taken and controls the sorting process. The controller also has to monitor the output, adjust the waste flow if necessary and communicate with other systems.

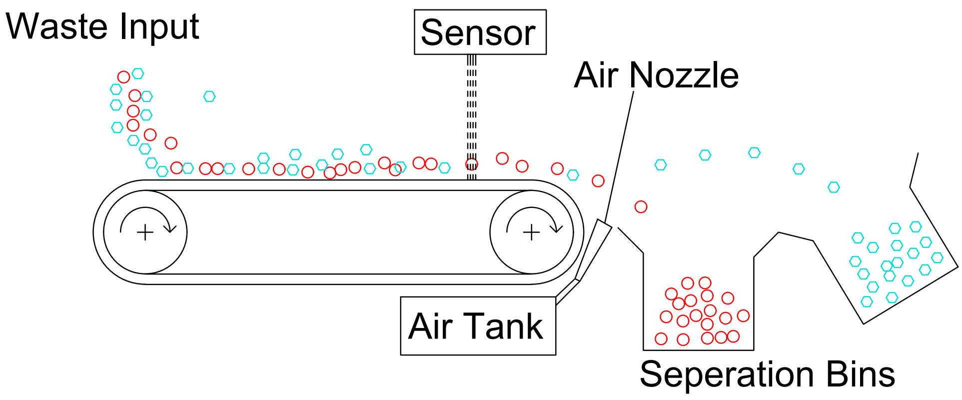

Figure 4.1: Schematic Overview of Optical Sorting System

All components are subject to constant scrutiny due to the ever-ongoing technological development. Therefore, different choices are available for specific applications. The following sections will present the available options and their particular applications.

4.2 Available Solutions for Optical Sensors

Depending on the operation requirements, there is a broad choice of optics bearing different advantages and disadvantages. Standard practice often requires the combination of multiple sensors to reach the desired result.

4.2.1 Visible Light Cameras / RGB Camera

Standard Red Green Blue (RGB) cameras are ideal not only for colour but also for pattern and shape recognition. Since RGB Cameras are not able to gather any information about the actual material, these systems are often deployed to detect and sort out specific items like plastic bottles, bottle caps or other objects with a distinct shape. RGB Cameras are also cheap and very efficient, which makes them attractive for industrial use.

4.2.2 NIR Spectroscopy

Infrared light is described as light waves within the range of 780nm - 1mm. The near-infrared spectrum lies in the band nearest to the visible light. It is not a concrete term but is usually defined within the range of 780nm - 2500nm. NIR exploits the effect that the molecular structure of a material has on reflecting NIR light. Materials create a unique signature based on how strongly they reflect specific light frequencies.

4.2.3 MIR / FTIR Spectroscopy

As the name suggests, the mid-infrared light spectrum is located above the NIR field. It is generally defined in the range of 2.5µm - 25µm. Where NIR systems detect the harmonic vibrations of the molecules in a material, the Mid Infrared (MIR) system detects the fundamental frequency and is, therefore, an order of magnitude more precise [19]. Table 4.1 gives a quick comparison between the two methods.

Feature	**Near Infrared (NIR)**	**Mid Infrared (MIR)**
Wavelength Range	$\sim$0.78 to 2.5 μm	$\sim$2.5 to 25 μm
Vibrations Detected	Overtone and combination vibrations	Fundamental molecular vibrations
Chemical Information	General functional groups; less specific	Rich, detailed chemical analysis
Penetration Depth	Deeper into samples	Shallow; more surface-sensitive
Material Identification	Good for known plastics (PET, HDPE)	More precise; for similar polymers
Speed & Usecase	Fast, real-time, conveyor-friendly	Slower, used offline or in lab analysis
Cost and Complexity	Lower cost, easier integration	Higher cost, more complex systems

Table 4.1: Comparison of NIR and MIR Spectroscopy in Material Analysis

Spectroscopy as a concept will be further examined as the practical part of this thesis project.

4.2.4 Hyperspectral Imaging (HSI):

Hyperspectral Imaging (HSI) is one of the most complex forms of optical analysis. Other than RGB cameras that only capture three bands of light, and even more complex than spectroscopy, which captures narrow bands of wavelengths, HSI captures multiple spectral bands in various ranges. Covering UV-light, all visible light and most of the IR spectrum, HSI operates in the range of 400nm to 2500nm.

4.2.5 Ultraviolet (UV) Imaging or Fluorescence:

Unlike IR imaging techniques, UV Imaging relies on exposure to UV light. This brings some advantages. Mainly the effect of Fluorescence. Materials exposed to UV light show patterns of absorption and reflection, but some materials emit longer frequencies. These frequencies can lie in the visible light spectrum, and some even rise to the IR spectrum. Therefore, this method can not only differentiate between material types but can also detect degrees of contamination. Liquids and oils show a very distinct fluorescence pattern; see liquid visualisation under UV light by criminal investigations.

4.3 Choice of Actuator

Separating certain particles from a waste stream can prove to be an extreme mechanical and electrical challenge. Systems need to be quick, precise, and low maintenance. These actuators are controlled by the electronic control unit, which processes input signals from the detection system and coordinates precise timing and movement for accurate separation of identified materials.

- **Compressed Air Ejectors (Air Jets)**: The most common type of sorting actuator is a compressed air ejector. It is comprised of either one movable nozzle or an array of nozzles across a waste stream conveyor. Exerting a jet of air at the correct time and position can eject an unwanted particle. This system is cheap, reliable, and low maintenance due to the low number of moving parts. One of the downsides is the narrow window of operation in terms of particle size and the unpredictability in the aerodynamic behaviour of these particles. Expelled air can also animate surrounding particles to move, even if they are not meant to be removed from the stream.
- **Robotic Arms / Grippers**: The most complex and precise actuators in use are robotic grippers. The system can very accurately move to a position, pick a waste particle, and separate it from the waste stream. Due to the added steps and movement paths, these systems induce delays in the sorting process. Robotic arms are, therefore, not used in high-volume MRFs.
- **Mechanical Diverters / Paddles / Pushers**: Mechanical diversifiers combine the simplicity of air jets with the precision of the robotic gripper. Quickly deployable paddles can divert particles into different directions or simply off a waste stream conveyor. These systems are often deployed in waste streams that are very uniform in size or narrowed down and singulated. Mechanical simplicity reduces the computational effort and allows for a more efficient sorting process. Another advantage of these mechanical diverters is the force that can be used to move even big and heavy objects that air streams would not affect.
- **Suction Systems**: Suction systems are more specialised tools and only work with a narrow range of objects. A movable arm with a soft rubber suction cup is placed on the object, and a vacuum is pulled through the cup. Due to the nature of a suction cup, the waste particles have to be in the correct range of size, shape and surface finish. Any deviation from the required aspects and the suction system is rendered useless. These systems are also volatile towards contamination. Moisture, any oil or dirt layer, will compromise the air seal's quality.

4.4 Available Options for Controller Unit

The choice for a processing unit of a sorting system is not made in a vacuum. These control units have to be compatible with other processing units of the MRF and be able to communicate accordingly. The choice of processing unit in an optical-based sorting system is critical, as it must handle real-time data processing from high-speed sensors such as cameras, spectrometers, or hyperspectral imagers.

Key considerations include processing power, maximal latency and the compatibility with sensor interfaces. Additionally, factors like energy consumption, thermal management, and scalability play a significant role, especially in industrial environments where 24/7 operation and integration with existing control systems are required. A lot of Waste sorting systems also utilise Artificial Intelligence Models, which also bring their own set of system requirements.

Programmable Logic Controler (PLC):
PLCs are the backbone of many industrial automation systems. These devices can execute basic tasks and build the base for larger operational systems. They are designed to process input signals, implement programs, and control output devices. Although many different manufacturers offer PLCs and each has exceptional capabilities, the basic structure remains the same. A PLC is task-driven and executes a continuous-loop logic program. Each loop is composed of these four distinct stages.

- **Input Processing:** Since PLC systems are simple control units, they can generally only process analogue and digital inputs. Digital inputs can range from simple user interface switches and buttons to digital sensors like laser light barriers.
- **Logic Program execution:** Logic programs that are developed for PLCs are usually proprietary to the manufacturer. Even after the standardisation under the IEC 61131-3, the programming format has a steep learning curve and is not compatible with modern languages like C++ or Python.
- **Signal Output:** Comparable to the inputs, PLCs are usually limited to analogue and digital signals. Examples of digital outputs are solenoids, relays, valves, motor starters, and alarms. Analogue outputs are typically implemented to control processes via fine adjustments like heat, motor speed and hydraulic actuators.
- **Maintenance Routine:** In the maintenance routine, the PLC communicates with higher-level control systems and exchanges information about the process. This section is also responsible for running diagnostic routines to log data.

PLCs are modular systems that can be tailored to a specific task. A whole system is referred to as a rack and can include the following components.

- **Central Processing Unit (CPU):** The Central Processing Unit (CPU) is the central part of the PLC and often the most expensive component. A balance between cost and processing power must be found; usually, an application-specific requirement.
- **I/O Modules:** These modules snap onto the rack and are usually easily interchangeable and therefore flexible in their deployment. These modules commonly offer 16, 32 or 64 individual inputs and outputs, respectively. They can also perform basic signal conditioning and adjust signal voltage levels to match the CPU's requirements. In addition to this conditioning, the units often provide an isolation layer between the CPU and the peripheral systems. Advanced models can carry out even more specialised tasks, like fault detection. Comparing inputs with expected values leads to increased reliability and decreased downtime for maintenance [20].

- **Communication Modules:** Communication modules are specialised components that can communicate with other PLCs, Supervisory Control and Data Acquisition (SCADA) systems, or even semi-intelligent peripheral devices. SCADA refers to top-level control and visualisation software that allows the monitoring of multiple PLCs [21]. Communication protocols range from simple serial communication like RS232 to sophisticated Ethernet protocols.
- **Human Machine Interface (HMI):** Human Machine Interfaces (HMIs) are deployed to represent essential data to a person to monitor a single PLC. Mission-critical metrics like system temperatures, motor speeds, and other metrics can be displayed and adapted through HMIs.
- **Miscellaneous:** PLCs need additional modules that don't add any productivity but are essential, like power supplies and other infrastructural modules. Most PLCs run on 24VDC, and power supplies are usually rated at about 5- 10A.

Software development for PLC

Software development for PLC is very different from modern software development in languages like C or Python. PLC Software is written and developed in one of 5 Languages and later translated to machine code and transferred to the PLC memory. Early on, every vendor of PLCs developed their proprietary language, but due to safety concerns, the IEC introduced the IEC 61131-3 standard and defined 5 standard languages [22].
The 5 languages are:

- **Ladder Logic (LAD)**
- **Function Block Diagram (FBD)**
- **Instruction List (IL)**
- **Structured Text (ST)**
- **Sequential Function charts (SFC)**

Since PLCs are comparable to microcontrollers, and since they do not deploy an actual operating system, they are limited in their capabilities regarding modern advanced automation problems. PLCs are still used and developed in specific industries, but more capable computers are being replaced more and more.

Industrial Computer (IC):
Advancements in semiconductor technology have increased the computational power and decreased the cost of chips. This paved the way for the development of ICs that are capable of tasks that exceed the capability of standard PLC units. These include advanced HMIs, data gateways, and artificial intelligence applications. Additional processing equipment explicitly developed for ICs allows for even greater processing power and workload consolidation, and reduces the hardware needed in the MRF plants.

- **Graphic Processing Unit (GPU):** In consumer-grade PCS, Graphic Processing Units (GPUs) are usually limited to video rendering and graphics processing. In an industrial environment, GPUs are used for real-time video processing and graphical analytics. Since GPUs have become more advanced over the coming generations, they are also regularly deployed for complex processing tasks like AI-computing, simulation and high-performance data processing [23].
- **Tensor Processing Unit (TPU):** Tensor Processing Units (TPUs) are Aplication-Specific Integrated Curcuits (ASICs) what Google first developed to aid in AI processing. Google designed these Tensor ASICs for in-house Machine Learning (ML) projects in 2013. In 2018, they released TPUs to third parties [24].
- **Non-Volatile Memory Express Solid State Drive (NVMe SSD):** Instead of traditional memory drives that connect to the central processor via a Serial Advanced Technology Attachment (SATA) bus, Non-Volatile Memory Express Solid State Drive (NVMe-SSD) memory directly connects to the PCI Express connectors. This allows for extremely low latency and data transfer upwards of 700 MB/s. Compared to regular memory drives that cap out at around 500 MB/s, in addition to a higher latency. NVMe-SSDs allow systems to process a lot more data in a shorter time, ensuring that all processes can run at maximum efficiency [25].

Durability and Versatility

Unlike consumer-grade computers, ICs are engineered to endure harsh industrial conditions, including extreme temperatures and mechanical stress. Key features include fanless operation, robust chassis construction, and legacy support for interfaces such as COM ports, M12 connectors, and GPIOS. This makes ICs highly adaptable to existing and future industrial systems.

Operating Systems and Performance

PLCs operate on specialised real-time operating systems tailored for deterministic control without requiring antivirus software. ICs, by contrast, uses general-purpose operating system like Windows or Linux, offering greater versatility and increased exposure to cyber threats.

Programming Paradigms

PLCs are generally programmed using scan-based routines and IEC-compliant languages. PLCs support modern programming languages such as C/C++ and .net, enabling more accessible development and broader compatibility.

Security Aspects

Both systems face cybersecurity challenges. While PLCs have traditionally been isolated, incidents like Stuxnet have revealed vulnerabilities. Stuxnet was a malicious program that focused on SCADA systems. It is believed to have substantially inflicted damage on the Iranian nuclear systems back in 2010. Since ICs are often monitored and accessed through online channels, they are subject to higher-level attacks. For this reason, ICs usually incorporate encryption hardware (e.g., TPM 2.0) and software firewalls to address these threats.

4.5 Artificial intelligence (AI) for optical waste sorting

ML is a branch of AI in which a system is trained on a set of data. After a model is trained, its task is to make predictions. The more data available for training, the more accurately the ML will execute the given task. The machine will then usually respond with an answer to the problem and a corresponding confidence value. This value describes the statistical probability that the machine came to the correct conclusion. There are three distinct kinds of training for a ML model [26].

Supervised Learning

In supervised learning systems, the machine is provided with input learning data in addition to tags or labels. These datasets are complex to generate and require a lot of human labour. Only humans can execute this task to exclude contamination through wrong labelling. Once a supervised learning system is finished, it will no longer adapt itself and will stay static. The two most common tasks carried out by supervised learning ML systems are classification and regression.

- **Classification:** The most basic task of classification is the distinction between different patterns. For example, if an AI is trained to recognise whether there is a cat or a dog in a given picture. The first step is to train the system with appropriate data. 500 pictures of dogs and 500 pictures of cats are shown to the system, and the system is told what animal is seen on each. The machine will iteratively adapt its network to classify these pictures. After the machine has learned all of the data, a new, previously unknown picture is shown to the system. The AI now calculates its answer based on its 1.000 past data points.
- **Regression:** A regression model prediction is analogous to the classification model. It does not predict if a data set is in one of two states; it usually predicts a numerical value. A basic example would be the prediction of customers who will buy a particular product within a specific timeframe. The data this system learns from is past product sales information and could include different attributes like time of year, location of the store, etc., including the corresponding labels, meaning the actual sale numbers. Based on this data, the AI will produce a certain number based on the new data.

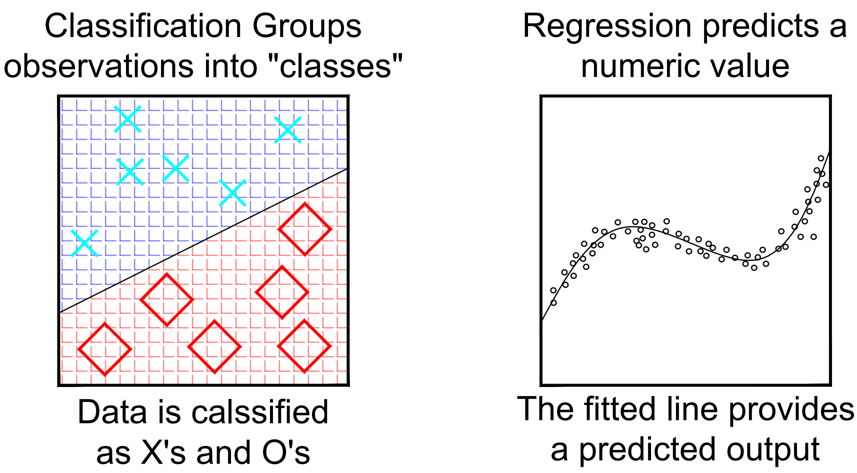

Figure 4.2: Classification vs. Regression

After an ML is trained in this manner, it will not change its behaviour based on later data sets. This increases the integrity of the system because no manipulated data can alter future behaviour. It also means that the system will not be able to react to future developments and consider current changes.

Unsupervised Learning

Unsupervised learning is a branch of machine learning where the algorithm works with data that has no labeled outputs. Unlike supervised learning, where models are trained on input-output pairs, unsupervised learning algorithms try to find hidden structures or patterns directly from the input data. The most common tasks in unsupervised learning include clustering and dimensionality reduction. Clustering algorithms, such as k-means or hierarchical clustering, group data points that are similar to each other, helping to reveal natural groupings in the data. Dimensionality reduction techniques, like Principal Component Analysis (PCA), reduce the number of features in a dataset while preserving as much information as possible, which is helpful for visualisation and reducing computational complexity. Unsupervised learning is often used for exploratory data analysis, anomaly detection, and feature learning.

Reinforcement Learning

Reinforcement learning is a type of machine learning where an agent learns to make decisions by interacting with an environment. Instead of learning from labelled data, the agent receives feedback in the form of rewards or penalties based on its actions. The goal is to discover a policy—a strategy for choosing actions—that maximises the cumulative reward over time.

Reinforcement learning is based on trial and error. The agent tries different actions, observes the outcomes, and gradually improves its behaviour through experience. This process is typically modelled

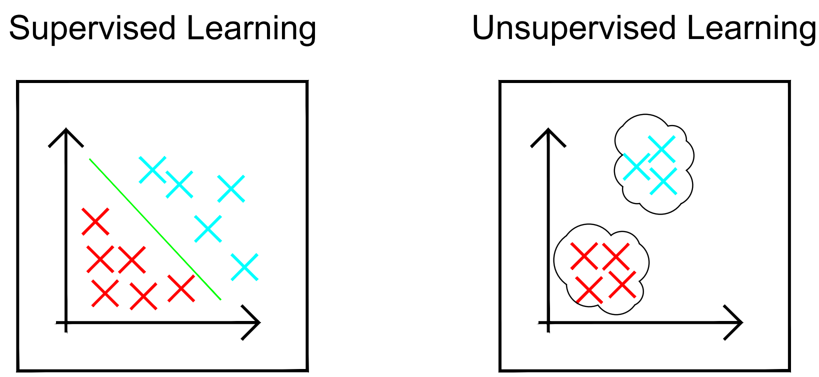

Figure 4.3: Supervised vs. Unsupervised Learning

using a Markov Decision Process (MDP), which includes states, actions, transition probabilities, and rewards. Key algorithms in reinforcement learning include Q-learning and policy gradient methods.

Reinforcement learning is beneficial when decisions need to be made sequentially and where the consequences of actions unfold over time. Typical applications include robotics, game playing, and autonomous systems.

4.5.1 Machine Learning (ML) for optical sorting

Optical sorting systems, regardless of their application, are usually classification models. Due to the amount of waste particles and forms of identifiable waste, these models are generally a combination of supervised and unsupervised learning models. The base training is established by a given data set. While this only sets the basis for the AI's behaviour, most systems are able to evolve and adapt over time. Another approach would be to train the model via the unsupervised learning method. By watching and scanning a waste stream, the system would pick up on patterns and clusters of waste particles that regularly turn up. With human feedback, these clusters could be identified as desirable sorting groups and used to separate by material, size or other attributes.

4.5.2 Differences to conventional systems

Machine learning is used in many processes that traditionally rely on human labour. In waste sorting applications, ML-based systems are more efficient and decrease the need for human labor in dangerous work environments. An article published in 2025 compared ML systems to conventional systems. The researchers examined the technological and economic differences between the contrasting approaches [27].

Technological Differences

- **Granulation:** As previously discussed, the first step in the majority of waste sorting plants is the granulation process. Where large chunks of waste are turned into small, more manageable pieces. While allowing for easier sorting for human labourers, this process actually increases the amount of material in a waste stream. AI-powered automated systems can identify and process large amounts of waste. In some instances, the granulation step can be skipped as a whole.
- **Material Separation by Size:** Both methods employ vibrating and trommel screens to separate materials based on size. However, in conventional systems, human labour often assists this process. Machine Learning Assisted Systems (MLASs) utilise these screens without direct human intervention.
- **Material Identification:** A significant technological difference lies in the use of advanced sensors (optical and NIR) in MLASs. These systems precisely identify materials based on their optical properties and chemical composition. Conventional systems lack such advanced sensor systems.

Econommical Differences

- **Initial Investment:** The initial investment for ML-based systems is significantly higher compared to conventional systems. High-end sensor equipment, industrial computers, and the complete technological infrastructure are major cost factors.
- **Operating Costs:** In contrast to the initial investment, the operational costs of AI systems are the driving factor for the switch to these systems. The study showed that over seven years, the ML-based system was almost 50% more cost-effective than conventional systems.

5 Density Seperation

The simplest form of density separation is a float-sink test, in which different materials are brought together in a fluid medium. The density of the medium lies between the densities of the samples; thus, one kind of sample floats while the other sinks. This method is the basic idea for density separation, but is somewhat imprecise and impractical.

5.1 Magnetic Density Separation (MDS)

Agnetic Density Seperation (MDS) is a material sorting technique that uses differences in material densities by mixing samples in a paramagnetic fluid exposed to an electromagnetic field. In a regular sink-float separation, the density of the fluid has to be a specific value for two materials to separate. This can lead to complications because a specific fluid must be produced for every pair of separating densities. Furthermore, the densities of the materials can't be too close to each other for the process to work correctly. The fluid in MDS applications can be tuned to a specific density to solve these complications. Therefore, the system can be altered to separate different materials quickly, and materials that have very similar densities can also be used, which is especially useful in the use case of plastics and non-ferrous metals.

By externally applying a magnetic force on a paramagnetic medium, which can align with external magnetic fields, it can change its density. The medium can be tuned not only to a specific density but also to a gradient of density. This way, not only can two materials be separated (float-sink), but more materials can be separated and will float in layers of their specific density.

5.2 Historical Development

The foundational physics of magnetic fluids and magnetohydrodynamics was established in the mid-20th century, but their application to material separation came much later. Research into the practical use of MDS began gaining momentum in the 1990s, driven by the need for more efficient and precise recycling techniques.

One of the pioneering regions in the development of MDS technology was the Netherlands, particularly through collaborative efforts between academic institutions like Delft University of Technology and industrial innovators. Companies such as Umincorp (Urban Mining Corp) played a key role in scaling the technology from laboratory research to industrial application, particularly for sorting complex post-consumer plastic waste streams.

By the early 21st century, MDS had become a promising alternative to traditional mechanical or thermal separation processes, especially in contexts where sustainability and material recovery are of growing importance.

5.3 Mechanics and Process Description

The MDS process consists of several key components and stages:

1. **Magnetic Fluid:** The separation medium is a paramagnetic fluid, usually a mix of water and manganese dichloride or other similar materials. These media are generally very stable and safe, which is vital if in contact with other reactive materials, as some plastics can be. They are also very responsive to externally applied magnetic fields.
2. **Magnetic Field Generation:** A magnetic field with a high-gradient characteristic is applied to the fluid. The medium exhibits a variable density from the bottom to the top of the container equal to the gradient of the magnetic field.
3. **Particle Introduction:** Material particles, such as shredded plastics or electronic waste fragments, are introduced into the fluid. Each particle migrates to the vertical level at which its actual density equals the fluid's apparent density under the influence of the magnetic field.
4. **Stratified Separation:** As a result, particles become suspended at different vertical positions according to their density. This stratification enables precise separation of materials with minimal overlap.
5. **Material Collection:** Separated materials are extracted mechanically using scoops, rotating drums, or belt systems. Each layer is removed at a different depth, corresponding to a specific material type.

5.4 Advantages and Applications

MDS offers several benefits over traditional separation techniques:

- **High precision:** Capable of separating materials with density differences as small as 0.01 g/cm^3.
- **Non-destructive:** Does not require melting, shredding or chemical treatment.
- **Environmentally friendly:** Avoids the use of toxic chemicals and minimises waste.
- **Scalable:** Suitable for both laboratory research and large-scale industrial applications.

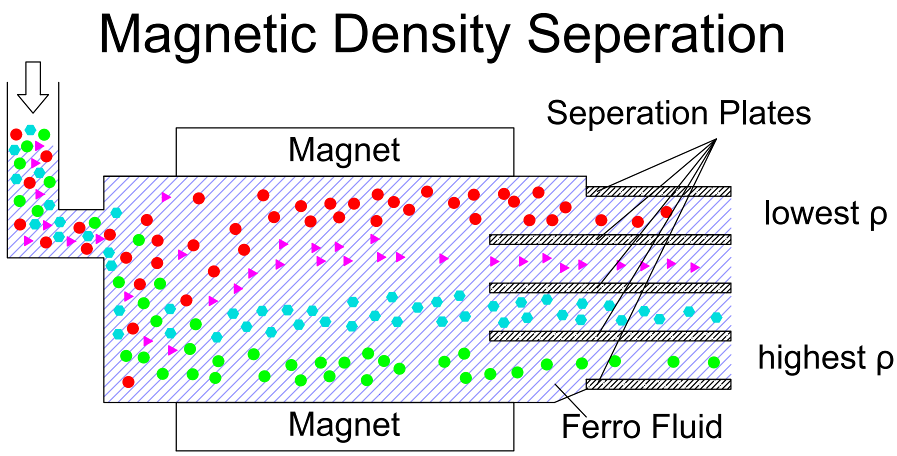

Figure 5.1: A schematic representation of the magnetic density separation setup

- **Effective for complex waste streams:** Particularly useful in recycling mixed plastic waste and separating non-ferrous metals.

5.5 Current and Future Use Cases

MDSs are increasingly being adopted in the plastic recycling industry, where traditional density separation methods struggle to distinguish between closely related polymers such as HDPE and PP. Future improvements in magnetic fluid formulation, magnet technology, and process automation are expected to make MDSs more efficient and cost-effective.

Beyond recycling, MDS holds potential in fields such as mineral processing, electronic waste recovery, and even in biomedical applications where precise material separation is required without mechanical damage.

5.6 Evalutaion based on the use case of 3D-printing labs

This section evaluates MDS based on five key criteria relevant to material discrimination in recycling and sorting technologies.

5.6.1 Cost

Assessment: Moderate to High

MDS systems involve moderate to high initial investment due to the use of specialized equipment such as high-strength permanent magnets or electromagnets, corrosion-resistant separation chambers, and paramagnetic fluids. Although operational costs are lower than thermal or chemical separation methods, maintenance of the magnetic fluid and system calibration requires recurring expenses. Compared to traditional float-sink separation, MDS is more expensive, but it remains cost-effective when high sorting precision is required.

5.6.2 Accuracy and Efficiency

Assessment: High

MDS provides excellent separation resolution, capable of distinguishing materials with density differences as small as 0.01 g/cm^3. This makes it especially useful for sorting plastics such as HDPE, PP, ABS, and PS. Industrial-scale MDS systems can achieve material purities of 95–99% and process several tons of material per hour. This high throughput, combined with its non-destructive nature, makes MDS a reliable and efficient method for high-value recycling applications.

5.6.3 Small-Scale Reproducibility

Assessment: Low to Moderate

Although the theoretical foundation of MDS is well established, reproducing the method on a small scale presents practical challenges. Laboratory implementation requires controlled generation of high-gradient magnetic fields, accurate preparation of paramagnetic fluids, and precise flow dynamics. These technical and material requirements may be difficult to meet in typical university laboratories or small research facilities. As a result, small-scale experimentation is possible but not straightforward without significant infrastructure.

5.6.4 Environmental Impact

Assessment: Positive

From an environmental perspective, MDS is a favourable option. It does not rely on toxic chemicals or solvents, and it solely depends on stable solutions that are not harmful.

6 Spectroscopy

Spectroscopy is a powerful analytical technique used to study the interaction between matter and electromagnetic radiation. By splitting light into the wavelengths it is made up of, one can detect changes before and after hitting different surfaces. This is not only utilised in material canalises but also in other fields like physics and biology, for instance. This chapter explains the basic principles of spectroscopy. Additionally, the different types of this technique are explored and their usage evaluated with a focus on material analysis.

6.1 Basic Understanding of light

The basic understanding of light and its components was developed in the 17th century. Isaac Newton's experiments with prisms in the 1660s demonstrated that white light could be separated into a spectrum of colours, laying the foundation for the understanding of light as a mixture of different wavelengths. Newton's work provided the first evidence that light behaves as a wave, although the exact nature of these waves remained unclear for over a century. Nearly 200 years later, the Fraunhofer lines were discovered as seen in figure 6.1. These lines appear in specific wavelengths of sunlight, which are absorbed by the sun's composition of elements. This was the first indication that the wavelength of light can used to differentiate between different components and materials [28].

// The real birth of spectroscopy as a scientific tool came in the mid-19th century with the work of Gustav Kirchhoff and Robert Bunsen. In 1859, Kirchhoff and Bunsen showed that each chemical element emits light at characteristic wavelengths when heated, creating a unique spectral "fingerprint." This allowed for the identification of elements based on the analysis of their emission spectra. Their work laid the foundation for atomic spectroscopy and provided an early method for identifying the composition of unknown substances.

Spectroscopy continued to evolve throughout the 19th and early 20th centuries, with the development of more sophisticated spectroscopic instruments and methods. The invention of the spectroscope,

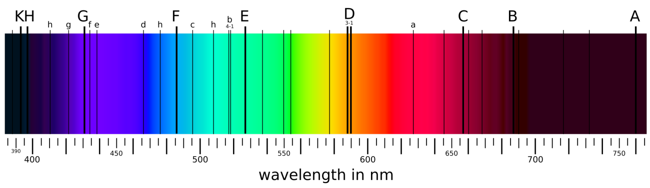

Figure 6.1: Frauenhofer Lines

a device that disperses light into its component wavelengths, allowed scientists to study spectra in greater detail. During this period, spectroscopy became a crucial tool in fields such as astronomy, where it was used to analyse the chemical composition of stars and distant galaxies.

6.1.1 Quantum Theory and the Expansion of Spectroscopic Techniques

The early 20th century saw significant theoretical advancements in spectroscopy with the advent of quantum mechanics. In 1913, Niels Bohr introduced his model of the atom, which explained the discrete energy levels of electrons and the corresponding spectral lines emitted by atoms. This led to a deeper understanding of atomic and molecular spectra and allowed for more accurate predictions of spectral behaviour.

With the development of quantum mechanics, new forms of spectroscopy emerged. The introduction of quantum theory enabled scientists to understand phenomena such as rotational, vibrational, and electronic transitions in molecules. This paved the way for the development of techniques such as IR spectroscopy, Raman spectroscopy, and Nuclear Magnetic Resonance (NMR) spectroscopy. These methods expanded the scope of spectroscopy, enabling researchers to study not only atoms but also molecules and their interactions.

6.2 State-of-the-Art in Spectroscopy

Today, spectroscopy is used in a variety of fields, each of which requires different characteristics for its measurements. A lot of different branches of science, therefore, developed their own specialised methods and equipment. In the following list, some types of spectroscopy are explained further, though there are many more:

- **Infrared (IR) Spectroscopy**: IR spectroscopy is used to study molecular vibrations by measuring the absorption of infrared light by a sample. The resulting spectra provide information about the chemical bonds and functional groups within a molecule. IR spectroscopy is widely used in organic chemistry to identify compounds and monitor chemical reactions. It is also very common in the recognition of differences in inorganic materials like plastics.
- **Ultraviolet-Visible (UV-Vis) Spectroscopy**: UV-Vis spectroscopy measures the absorption or transmission of ultraviolet and visible light by a sample. It is commonly used to study electronic transitions in molecules and is valuable for analysing compounds with conjugated systems, such as organic dyes and pigments. It is also a key technique in biological studies for analysing DNA, proteins, and other biomolecules. The most usefull apsect of UV-analysis is the luminescence, which happens when a material is exposed to UV-light and subsequently emmits a light with a different energy state or wavelength which is actually visible by the human eye. This technique is also used to make the remains liquid visible [19].

- **Raman Spectroscopy**: Raman spectroscopy is based on the inelastic scattering of light (Raman scattering), where photons interact with the vibrational modes of molecules. Unlike IR spectroscopy, which measures absorption, Raman spectroscopy measures scattered light and provides complementary information about molecular vibrations. This technique is used in material science, chemistry, and even forensic analysis. This analysis can also be utilised in plastic recognition and will be further analysed later in this chapter.
- **Nuclear Magnetic Resonance (NMR) Spectroscopy**: NMR spectroscopy uses the interaction of nuclear spins with an external magnetic field to provide detailed information about the structure of molecules. Nuclear Magnetic Resonance Spectroscopy (NMRS) is an essential tool for determining the structure of organic compounds and biomolecules, such as proteins and nucleic acids, and is extensively used in both academic research and pharmaceutical development [29].
- **X-ray Spectroscopy**: X-ray spectroscopy techniques, such as X-Ray Flouresence (XRF) and X-Ray Absorbtion Spectroscopy (XAS), are used to study the elemental composition and chemical state of materials. X-Ray Diffraction (XRD) is another powerful tool used to analyse crystal structures. X-ray spectroscopy is widely used in geology, materials science, and environmental analysis.

Each of these techniques offers unique advantages and can be applied to different types of samples, making spectroscopy a versatile and essential tool in modern science.

6.2.1 Interaction of Light with Matter

When light interacts with matter, several processes can occur, including absorption, emission, reflection, and scattering. The specific outcome depends on the nature of the material and the wavelength of the incident light.

- **Absorption**: At certain wavelengths, photons can be absorbed by the material, causing transitions of electrons to higher energy states. The wavelengths at which absorption occurs are characteristic of the specific elements and molecular bonds within the material. This process can be described by Beer-Lambert Law, which relates the absorption of light to the properties of the material through which the light is traveling.
- **Emission**: After absorbing energy, atoms and molecules may return to their ground states by emitting photons. The wavelengths of these emitted photons are indicative of the energy levels of the emitting species. Emission spectroscopy, such as Atomic Emission Spectroscopy (AES) and fluorescence spectroscopy, capitalizes on this principle.
- **Reflection and Scattering**: Light may also be reflected or scattered by materials. Reflection involves the bouncing of light off the surface, while scattering involves the redirection of light in different directions. Scattering can be elastic (Rayleigh scattering) or inelastic (Raman scattering), with the latter providing insights into molecular vibrations and rotational transitions.

6.2.2 Measurement of Wavelengths Using a Spectroscope

A spectroscope is an instrument designed to measure the spectrum of light. It works by dispersing light into its constituent wavelengths and detecting the intensity of light at each wavelength. The basic components of a spectroscope include:

- **Light Source**: Provides the initial beam of light, which can be broad-spectrum (e.g., a tungsten lamp) or monochromatic (e.g., a laser).
- **Sample Holder**: Where the material under study is placed. The light interacts with the sample, and its properties are altered based on the material's characteristics.
- **Dispersive Element**: This component, often a prism or diffraction grating, spatially separates light into its component wavelengths. A prism refracts light at different angles depending on the wavelength, while a diffraction grating uses interference to achieve dispersion.
- **Detector**: Captures the dispersed light and measures its intensity at different wavelengths. Common detectors include Charged-Couple Devices (CCDs), Photomultiplier Tubes (PMTs), and photodiodes.

The spectroscopic data is often represented as a spectrum, a plot of light intensity (or another quantity related to light) as a function of wavelength. The position and intensity of peaks within the spectrum provide critical information about the sample, such as its chemical composition, molecular structure, and physical properties.

6.3 Methodology

To prove, test, and quantify the results of this project, multiple types of plastics are analysed under different conditions. The methodology involves placing a sample of material in various lighting environments and measuring the reflected light waves. To ensure that all measured data is accurate, all variables except the material itself have to be constant between samples. All Samples are printed in the same orientation, resulting in the same surface finish and dimension.

6.3.1 Material Samples for Measurement

Given that this project focuses on recycling for 3D printing purposes, the materials selected as samples are those commonly available and actively used in 3D printing. The samples are manufactured using 3D printing technology. Each sample is standardised to a shape of a 5 cm x 5 cm square plate with rounded corners and a thickness of 5 mm.

6.3.2 Experimental Procedure

The experimental procedure consists of the following steps:

- **Sample Preparation**: All samples are prepared using the same 3D printing parameters to ensure uniformity in surface finish, shape, and size. This standardisation is crucial to eliminate any variations that could affect the spectroscopic measurements.
- **Lighting Conditions**: Each sample is placed in different lighting environments to analyse how various light conditions impact the spectral characteristics of the material. The lighting conditions will include, but are not limited to, natural daylight, fluorescent lighting, and LED lighting.
- **Spectroscopic Analysis**: A spectroscope is used to measure the spectrum of light reflected, absorbed, and transmitted by the samples. The spectroscopic data are recorded and analysed to identify the unique spectral signatures of each type of plastic under different lighting conditions.
- **Data Collection and Analysis**: The data collected from the spectroscopic measurements are processed to quantify the optical properties of the samples. This includes determining the wavelengths at which significant absorption, reflection, and transmission occur, and how these properties vary with different lighting conditions.
- **Comparison and Validation**: The results are compared against known standards and literature values to validate the accuracy and reliability of the measurements. Any discrepancies are analysed to identify potential sources of error or variation in the experimental setup.

6.3.3 Standardization and Controls

To ensure the reliability and reproducibility of the results, several control measures are implemented:

- All samples are manufactured using the same batch of material to avoid any batch-to-batch variation.
- The 3D printer settings, including print speed, temperature, and layer height, are kept constant across all samples.
- The spectroscope is calibrated before each set of measurements to maintain consistency in the spectral data.
- Environmental factors, such as temperature and humidity, are monitored and controlled during the experiments to minimise their impact on the results.

By following this rigorous methodology, the project aims to provide a comprehensive analysis of the spectroscopic properties of different plastics used in 3D printing under various lighting conditions. This will facilitate the development of reliable and standardised methods for the recycling and reuse of 3D printing materials.

6.4 Raman Spectroscopy Method

Raman spectroscopy is a powerful analytical technique used to gain insights into the molecular composition and structure of materials. It is beneficial for identifying organic and inorganic compounds, making it an ideal method for analysing the plastic samples in this project.

6.4.1 Principle of Raman Spectroscopy

Raman spectroscopy is based on the inelastic scattering of monochromatic light, typically from a laser, by molecules in a sample. When the laser light interacts with the sample, most photons are elastically scattered (Rayleigh scattering), meaning they scatter without a change in energy. However, a small fraction of the photons are inelastically scattered (Raman scattering), resulting in a shift in energy corresponding to the vibrational modes of the molecules in the sample.

The Raman effect occurs due to the interaction of the incident light with the vibrational energy levels of the molecules. The energy difference between the incident and scattered photons provides a unique fingerprint for the molecular structure and composition of the sample.

6.4.2 Advantages of Raman Spectroscopy

Raman spectroscopy offers several advantages for the analysis of plastic materials:

- **Non-Destructive**: Raman spectroscopy is a non-destructive technique, allowing samples to be analysed without causing any damage.
- **Minimal Sample Preparation**: Unlike some other spectroscopic techniques, Raman spectroscopy requires minimal sample preparation, making it convenient and efficient.
- **High Specificity**: The Raman spectra provide unique fingerprints for different molecular structures, allowing for precise identification of materials.
- **Compatibility with Water**: Raman spectroscopy is less affected by water, making it suitable for analysing hydrated samples.

In conclusion, Raman spectroscopy is an invaluable tool for the detailed analysis of plastic samples in this project. By leveraging the unique vibrational signatures obtained through Raman scattering, this method provides a comprehensive understanding of the molecular composition and structure of 3D printing materials, aiding in the development of effective recycling strategies.

6.5 Near-Infrared Spectroscopy Method

NIRS is a non-destructive analytical technique widely used for characterising the composition of various materials. It is particularly effective in identifying organic compounds, making it a valuable tool for analysing the plastic samples in this project.

6.5.1 Principle of Near-Infrared Spectroscopy

NIRS operates on the principle of absorption spectroscopy in the near-infrared region of the electromagnetic spectrum, typically between 780 nm and 2500 nm. When near-infrared light interacts with a sample, specific wavelengths are absorbed by the molecular overtones and combinations of fundamental vibrations of the sample's constituent molecules. The absorption pattern, or spectrum, produced by these interactions provides a unique fingerprint that can be used to identify and quantify the different chemical components within the sample.

6.5.2 Experimental Setup

The experimental setup for NIRS includes the following components:

- **Light Source**: The near-infrared light source, often a tungsten-halogen lamp, provides the necessary illumination. The light emitted covers the near-infrared range, ensuring comprehensive analysis.
- **Sample Holder**: The sample is placed in a holder that can accommodate various sample types and sizes. For this project, plastic samples are prepared in standardised dimensions to ensure consistency.
- **Optics**: Lenses and mirrors direct the near-infrared light through the sample and onto the detector. The setup ensures that the light path is optimised for maximum interaction with the sample.
- **Detector**: The transmitted or reflected light from the sample is captured by a detector, typically an InGaAs (Indium Gallium Arsenide) detector, which is sensitive to near-infrared wavelengths. The detector converts the light into an electrical signal that corresponds to the intensity of the absorbed wavelengths.
- **Data Processing**: The electrical signal is processed to generate a near-infrared spectrum, representing the absorbance of different wavelengths by the sample. This spectrum is analysed to identify and quantify the molecular components.

6.5.3 Procedure

The procedure for conducting NIRS on plastic samples involves the following steps:

1. **Sample Preparation**: The plastic samples are cleaned to remove any surface contaminants that could interfere with the NIR signal. The samples are standardised to 5 cm x 5 cm square plates with a thickness of 5 mm to ensure consistency.
2. **Light Interaction**: The near-infrared light is directed onto the sample. The light that is either transmitted through or reflected off the sample is collected for analysis.
3. **Spectral Acquisition**: The detector captures the transmitted or reflected light and converts it into an electrical signal. This signal represents the intensity of light at various wavelengths.
4. **Data Analysis**: The resulting spectrum is analysed to identify characteristic absorption peaks. Each peak corresponds to specific molecular vibrations, providing detailed information about the sample's chemical composition.

6.5.4 Advantages of Near-Infrared Spectroscopy

NIRS offers several significant advantages for the analysis of plastic materials:

- **Non-Destructive**: NIRS can analyse materials and samples in a non-destructive manner, allowing the samples to be used indefinitely or the materials to be reused in another way.
- **Minimal Sample Preparation**: NIRS requires very little sample preparation, making it even more suitable for analysing 3D-printed materials. The process of 3D-printing, especially FDM, usually does not lead to a smooth surface finish. Even if the 3D printer is set up professionally, the surface can show signs of roughness or, depending on the orientation of the printed object, produce layer lines.
- **Rapid Analysis**: Depending on the exact setup, NIRS allows for rapid measurements and analysis of materials, which in turn promotes a high efficiency of mechanisms that rely on it.
- **High Penetration Depth**: Near-infrared light can penetrate deeper into samples compared to other spectroscopic methods, allowing for bulk analysis.
- **Compatibility with Various States**: NIRS is suitable for analysing samples in different states, including solids, liquids, and gels, making it a versatile analytical tool.

In conclusion, Near-Infrared Spectroscopy is a vital technique for this project's detailed analysis of plastic samples. By capturing the unique absorption patterns in the near-infrared region, NIRS provides a comprehensive understanding of the molecular composition and structure of materials used in 3D printing. This understanding is crucial for developing effective recycling strategies and supporting sustainable practices in the field of 3D printing and materials science.

6.6 3D-Printing

Since the main use case for this project is focused on 3D-printable materials and a significant number of parts for this project are 3D-printed, this section will explain the basics of this technology.

6.6.1 3D-printing technologies

3D printing is known as an additive production method, which means instead of removing material from an oversized blank of material like in classical machining, the material is applied bit by bit to form the desired shape. One of the most widely used methods is called FDM. In this method, a spool of filament is pushed through a heated nozzle. Several motors control the position and height of the nozzle. Layer by layer, the desired shape is produced on the building plate. In table 7.1, the most popular 3D-printing technologies are described and compared.

7 3D Printing

3D printing, also known as additive manufacturing, has revolutionised manufacturing by allowing the creation of complex structures and custom objects with high precision. The technology has found applications across various industries, including aerospace, automotive, healthcare, and consumer products. This chapter explores the historical development of 3D printing, the current state of the art, and future trends, focusing on materials, techniques, and the innovation potential.

7.0.1 Early Development of Additive Manufacturing

The concept of additive manufacturing, where objects are built layer by layer, dates back to the 1980s. Charles Hull filed the first patent for Stereolithography (SLA), a technique that uses ultraviolet light to solidify photopolymer resins, in 1984. This marked the birth of modern 3D printing, although high costs and slow printing speeds initially limited the technology. Hull's invention laid the groundwork for future advancements by demonstrating the feasibility of producing three-dimensional objects directly from digital models.

Following the success of SLA, other additive manufacturing technologies emerged, including Selective Laser Sintering (SLS) and FDM, both of which were patented in the late 1980s. While these early systems were primarily used for prototyping and research, they demonstrated the potential for 3D printing to disrupt traditional manufacturing processes by enabling on-demand production and the customisation of complex geometries.

Throughout the 1990s and early 2000s, 3D printing technology evolved, improving speed and material diversity. The introduction of lower-cost desktop 3D printers made the technology more accessible, particularly in industries like engineering, design, and education. The RepRap project, launched in 2005, further democratised 3D printing by developing an open-source 3D printer capable of printing many of its own components. This project spurred widespread interest in additive manufacturing and fostered a global community of makers and hobbyists.

During this period, industrial 3D printing systems also became more sophisticated, enabling the production of functional parts in sectors like aerospace and medical devices. Companies such as Stratasys and 3D Systems played a leading role in commercialising 3D printing technologies and broadening their applications. As patent expirations allowed more competitors to enter the market, 3D printing technology became more affordable and versatile.

7.0.2 Current 3D Printing Techniques

Today, 3D printing encompasses a wide range of techniques, each with strengths and limitations. The most common methods are SLA, FDM, SLS, and Digital Light Processing (DLP).

- **Stereolithography (SLA)**: SLA remains one of the most precise 3D printing techniques. It uses ultraviolet light to cure liquid resin, solidifying layers one at a time. SLA is particularly valued for its high resolution and smooth surface finish, making it suitable for detailed models and prototypes, especially in the medical and dental fields.
- **Fused Deposition Modeling (FDM)**: FDM is one of the most widely used 3D printing technologies, especially among hobbyists and small businesses. It works by extruding thermoplastic filaments, such as PLA or ABS, through a heated nozzle and depositing them layer by layer. FDM is popular due to its affordability and simplicity, though it typically produces lower-resolution prints compared to other methods.
- **Selective Laser Sintering (SLS)**: SLS uses a high-powered laser to fuse powdered materials, such as nylon or metal, into solid objects. This technique allows for creating durable and complex parts without the need for support structures, making it ideal for producing functional prototypes and low-volume production runs.
- **Digital Light Processing (DLP)**: DLP is similar to SLA in that it uses light to cure resin. However, instead of using a laser to trace each layer, DLP uses a digital light projector to project a whole image at once. This allows for faster print times, making it popular for applications where speed is critical, such as in the production of dental aligners or small-scale manufacturing.

Each of these techniques has found applications in industries ranging from healthcare to aerospace, depending on the specific requirements for material properties, resolution, and production speed.

7.0.3 Materials for 3D Printing

The range of materials available for 3D printing has expanded significantly, allowing manufacturers to choose materials tailored to specific applications. Early 3D printers were limited to a small selection of thermoplastics, but today, a wide variety of polymers, metals, ceramics, and even biological materials can be printed.

- **Polymers**: The most common materials used in FDM and SLA printers are thermoplastics like PLA, ABS, and Polycarbonate (PC). These materials are suitable for various applications, from consumer products to engineering prototypes. High-performance thermoplastics like polyether ether ketone (PEEK) and polyamide (Nylon) are used for more specialised applications.
- **Metals**: Metal 3D printing, typically done via SLS or Selective Laser Melting (SLM), has opened up new possibilities in industries such as aerospace, automotive, and medical implants. Materials such as titanium, stainless steel, and aluminium are commonly used for their strength and

durability. Metal 3D printing allows for the production of lightweight, complex parts that would be difficult or impossible to manufacture using traditional methods.

- **Ceramics**: Ceramic 3D printing, while still a developing field, has applications in engineering and art. Additive ceramics manufacturing is advantageous in industries requiring high-temperature resistance and hardness, such as electronics or aerospace.
- **Biomaterials**: 3D printing with biomaterials has garnered significant interest in the medical field, particularly in regenerative medicine and tissue engineering. Researchers have developed bioinks that can print living cells, creating scaffolds for tissue regeneration or even whole organs. While the technology is still in its infancy, bioprinting holds great promise for future medical applications.

7.0.4 Applications and Impact

The impact of 3D printing has been profound across multiple sectors. In healthcare, custom prosthetics, dental implants, and even surgical models are now routinely 3D printed, providing tailored solutions to patients while reducing costs and production times. In the aerospace and automotive industries, lightweight yet strong components produced via metal 3D printing have improved fuel efficiency and reduced lead times for prototype development.

In addition to industrial uses, 3D printing has also influenced the consumer market. The ability to create personalised products, from jewellery to phone cases, has given rise to a new wave of custom manufacturing, with small businesses and individual makers utilising desktop 3D printers to create bespoke items.

7.0.5 New Materials and Multi-Material Printing

One of the most exciting areas of development in 3D printing is the introduction of new materials, including composites, nanomaterials, and innovative materials. These advancements will enable 3D printers to produce parts with enhanced properties, such as greater strength, flexibility, or conductivity. Multi-material 3D printing, which allows for the simultaneous deposition of different materials, will also enable the creation of complex, functional parts, such as electronic devices or advanced medical implants.

Innovative materials that can change their properties in response to environmental stimuli (such as temperature or light) are also being explored for 4d printing applications. This technology could enable the production of objects that can self-assemble or change shape over time, opening up new possibilities in robotics, aerospace, and other fields.

7.0.6 Sustainability and Circular Economy in 3D Printing

Sustainability is becoming an increasingly important consideration in the future of 3D printing. The additive nature of 3D printing inherently produces less waste compared to subtractive manufacturing methods, where excess material is removed. Additionally, recycled materials are being integrated into 3D printing processes, further reducing the environmental impact of production.

There is also growing interest in using 3D printing to support a circular economy, where products are designed for reuse and recycling. For example, 3D printing allows for easy repair of broken components, reducing the need for full product replacements. In the future, local recycling facilities could process old products into raw materials for new 3D prints, closing the loop on material use.

7.0.7 Challenges and Limitations

Despite its many advantages, 3D printing still faces several challenges. Printing speed and build volume limitations restrict its use in mass production for specific industries. Additionally, the mechanical properties of 3D-printed parts, particularly those produced via FDM, are often inferior to parts made through traditional manufacturing methods. Research into improving material strength and print speed is ongoing.

Regulatory issues also present a barrier to widespread adoption in critical sectors like healthcare and aerospace. For example, ensuring the consistency and quality of 3D-printed medical devices or aeroplane components requires rigorous testing and standardisation, which can slow down innovation.

Table 7.1: Comparison of Popular 3D Printing Technologies

Technology	Description	Typical Applications
FDM (Fused Deposition Modelling)	uses thermoplastic filaments melted and extruded layer by layer.	Prototyping, hobbyist projects, and educational use.
SLA	utilises a UV laser to cure liquid resin into hardened plastic.	High-detail prototypes, jewellery, dental moulds.
SLS	uses a laser to sinter powdered material, binding it together.	Functional prototypes, complex geometries, and aerospace parts.
DLP	Cures resin using a digital light projector layer by layer.	High-resolution prints, dental applications, and jewellery.
Binder Jetting	Deposits a binder onto layers of powder to create parts.	Metal parts, sand casting molds, and large-scale prints.
Material Jetting	Sprays: droplets of material to build parts layer by layer.	Full-color prototypes, complex models, and tooling.
HP Multi Jet Fusion	utilises a printing process that fuses layers of powder with heat and ink.	Production parts, prototypes with functional properties.

8 Experimental Setup

The Spectrometer setup is based on an open-source project which uses a low-cost handheld spectroscope [30]. The PySpectroscope project is a program and an associated hardware design created for hobbyists to test homemade lasers and perform fluorescence spectroscopy. The setup consists of a camera equipped with an appropriate lens. The camera is fixed to a base, which aligns it with the handheld spectroscope, which is also fixed to the base. This assembly is pointed at a sample holder, which is oriented to hold the 3D-printed samples at a 45° angle. Lastly, a light source is fixed to an appropriate mount and pointed at the sample holder so that the light reflected off the sample shines directly into the spectroscope. The experiment setup was then mounted inside a plastic container, which can be sealed with a lid to ensure no external light can interfere with the measurement. The whole setup is described in the graphic below, and the physical setup is shown in the picture.

8.1 Components

As part of this project, all mounts for the physical components were designed and explicitly 3D-printed for this application.

8.1.1 Processing Unit

There are many considerations when choosing a processing unit for this application. The processing power has to be enough to process video data and perform calculations on medium-sized data sets. For this reason, any kind of PLC was not feasible. The following considerations have factored into the choice.

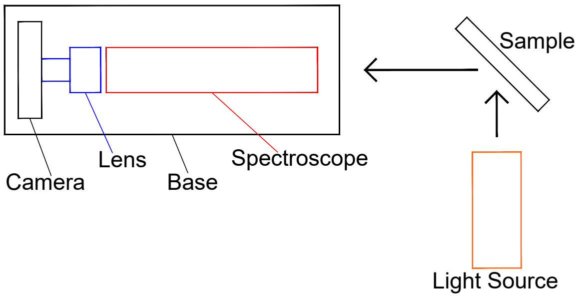

Figure 8.1: Diagram of spectrometer setup

Figure 8.2: Picture of spectroscope setup

- **Processing Power:** Many projects that aim for low-cost solutions rely on microcontrollers as their processing unit. Since this project is based around camera connectivity and graphical processing, a microcontroller was out of the question. This project focused on an actual microprocessor capable of running sophisticated operating systems.
- **Formfactor:** For this particular project, the size of the processor was not actually of any concern since it is just a proof of concept. For systems that are deployed in industrial environments, size would only be a factor for portable applications.
- **Compatibility** To ensure that all possible sensors and cameras can be used in combination with this computer, the I/O interface and integrated communication interfaces were of great importance. Easy access to a large number of GPIO pins and a dedicated camera interface is an important requirement for this development.
- **Support & Availiability** One of the most critical factors for educational projects like these is the customer support and the availability of the processor. Although customer support usually refers to support between the vendor and buyer, other forms exist. In the modern day of technology, a lot of people develop projects of their own and share their findings publicly. These communities provide excellent support for a lot of problems that can arise with any product.
- **Cost** This is a proof-of-concept project based in a university, so the processing unit could not exceed a specific price range. Luckily, many processors are well within an educational price range and well exceed the processing demands.

Based on these considerations, the processing unit for this application was chosen to be the Raspberry Pi 4 single-chip computer. This was also the basis of the reference project that this project follows.

Category	**Raspberry Pi 4 Characteristics**
Processing Power	Quad-core Cortex-A72 CPU @ 1.5GHz, up to 8GB RAM, capable of running a full Linux OS
Form Factor	Compact board (85.6mm x 56.5mm), suitable for embedded and portable projects
Compatibility	Broad support for Linux distros (Raspberry Pi OS, Ubuntu, etc.), compatible with GPIO-based hardware and HATs
Support & Availability	Large community support, extensive documentation, wide availability from online and local distributors
Cost	Affordable, ranging from $35 to $75 depending on RAM variant

Table 8.1: Raspberry Pi 4 – Key Characteristics

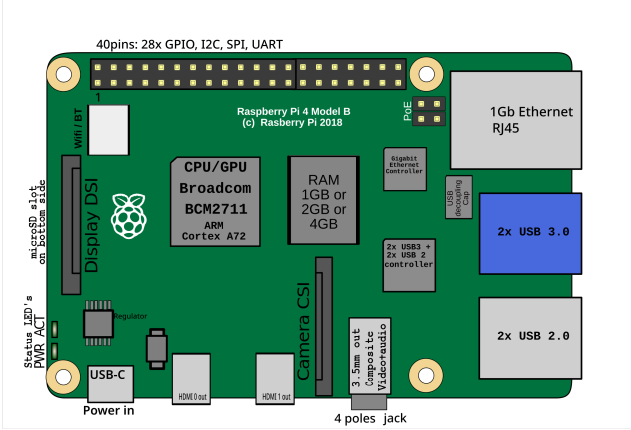

Figure 8.3: Raspberry Pi 4 Model B

Figure 8.4: Camera Module

8.1.2 Camera Module

The specifications for the camera module are mainly focused on resolution. The reference project recommended a Raspberry Pi-compatible camera with an adjustable focus length and 5mp resolution. The factory lens is mounted on the camera on an M12 metric thread, which is used to mount the additional magnification lens. For this project, two cameras were used. The first one is an 8mp Raspberry Pi cam as described in 8.2. The second one is a standard, no-name USB Webcam.

8.1.3 Spectroscope base and camera mount

The Spectroscope used in this project is a TE-313 [31] Diffraction Grating Spectroscope that is designed explicitly for Educational Science use as seen in figure 8.5. It can be used as a handheld

Specification	Details
Image Sensor	IMX219
Still Resolution	8 Megapixels
Sensor Resolution	3280 × 2464 pixels
Video Modes	1080p @ 47fps, 1640 × 1232 @ 41fps, 640 × 480 @ 206fps
Pixel Size	1.12 µm × 1.12 µm
Optical Size	1/4"
IR-Cut	Yes
Module Size	32mm × 32mm
Lens	FOV60, FOV90, FOV160 Options

Table 8.2: Camera Module Specifications

spectroscope to showcase different effects and changes in the spectral behaviour of light. When a camera is fixed to the spectroscope and the intensity of the other light levels is measured, it turns into a spectrometer, creating valuable data.

The spectroscope needed to be fixed to allow the user to rotate it along its cylindrical axis so that it can be oriented at the correct angle. When the proper position is reached the spectroscope can be fixed with a screw on top. The Camera needs to be mounted directly in line with the inner circular view window of the spectroscope. To achieve that, the spectroscope mount and the camera mount are fixed together on a 5 mm-thick copper plate to ensure a sturdy base.

8.1.4 Sample holder

The sample holder is also a 3D-printed part. Because of this, it had to be designed to minimise the amount of plastic that can be seen from the front so that the material of the sample holder does not interfere with the measurement of the actual sample. This is achieved by a spring-loaded design that clamps the samples between two thin jaws. This allows no material of the sample holder to be in front of the actual sample, and the whole surface to be presented to the spectroscope.

8.1.5 Light Source mount

8.1.6 4-in-1 Flashlight with Focus Function for Plastic Spectroscopy

The light source employed in this project is a high-performance, single-mode LED flashlight as seen in figure 8.9. It can produce a powerful light in a very white light, producing a broad spectrum of frequencies. Additionally, it can create red, blue and green in more concentrated frequency bands. This versatile flashlight is ideal for spectroscopic measurements of various plastic materials, providing a focused beam capable of covering distances over 120 meters. Its different light modes are critical for testing material response to multiple wavelengths.

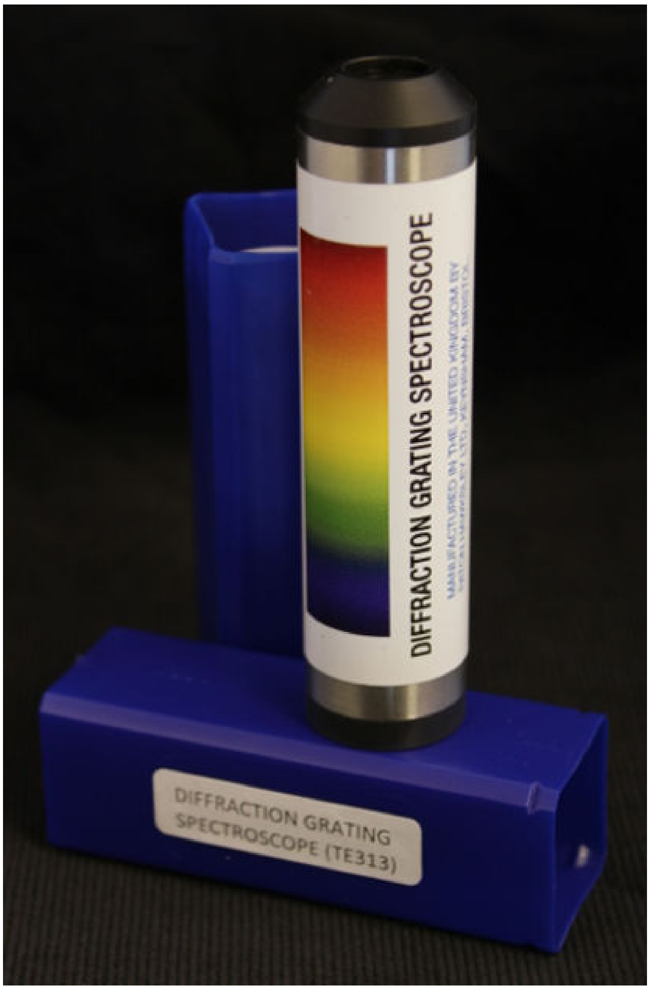

Figure 8.5: Diffracting Spectroscope [31]

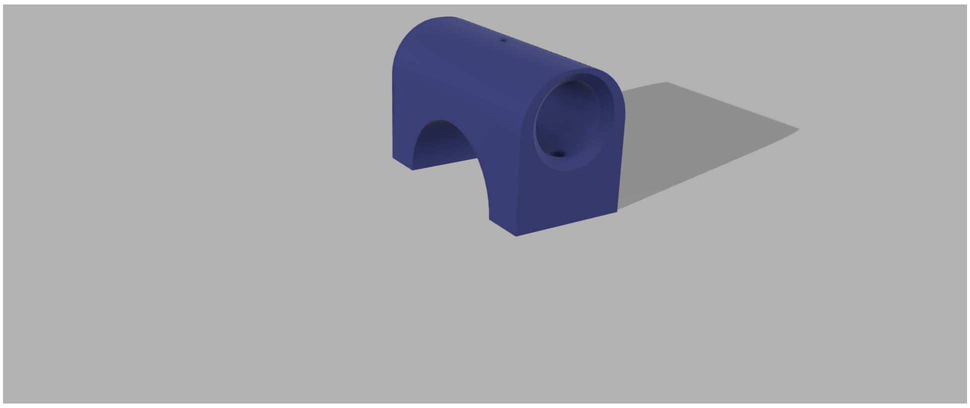

Figure 8.6: Spectroscope Mount 3D-Design

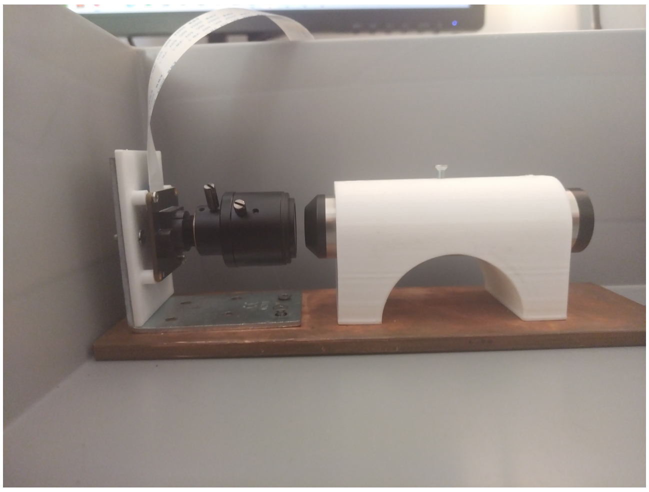

Figure 8.7: Spectroscope mount

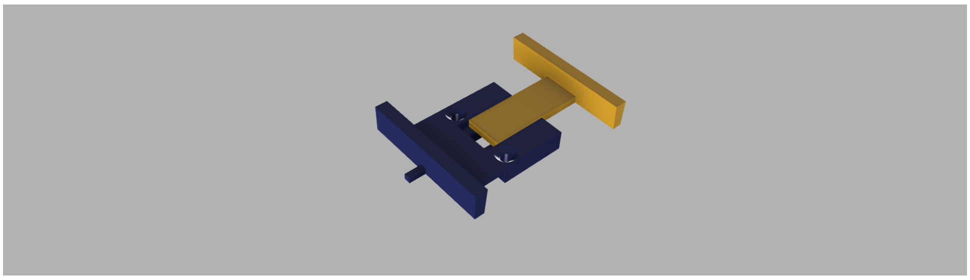

Figure 8.8: Sample holder 3D-Design

Figure 8.9: Light Source

Red and Green Light for Material Characterisation

In plastic spectroscopy, red and green light modes are used to observe different polymers' optical and molecular responses to these specific wavelengths. Plastics' varying absorption and reflection characteristics under red and green light can reveal necessary information about their chemical structure. This is particularly relevant in distinguishing between plastics with similar visible-light properties but different infrared or near-infrared responses. These modes allow for selective excitation of certain bonds or surface features, enabling precise analysis of material properties without causing sample degradation.

Blue Light for Fluorescent and Reflective Plastic Analysis

The blue light mode is particularly effective in fluorescence and reflectivity analysis of certain plastic materials. Many polymers exhibit fluorescence under blue light, which can be used to identify specific additives or coatings. The resulting fluorescence or reflective behaviour can be captured and analysed by illuminating the plastic samples with blue light. This method is beneficial for identifying trace materials or detecting surface treatments, where blue light excites certain molecular bonds to emit measurable light for further spectroscopic analysis.

Waterproof and Shockproof Design for Field and Lab Use

The flashlight's waterproof and shockproof design ensures its durability in both laboratory and field settings. Whether the experiment is conducted in controlled lab environments or in outdoor conditions, the rugged construction guarantees reliable performance. Its resistance to environmental factors like water and mechanical shock makes it suitable for extended experimental use in conditions that might otherwise affect more delicate equipment, ensuring uninterrupted spectroscopic measurements of plastic samples.

White Light for Baseline and Calibration Measurements

The white light mode serves as a general-purpose light source, beneficial for baseline measurements and calibration in spectroscopic analysis. Its broad-spectrum emission enables uniform illumination of plastic samples, providing a reliable reference point for comparative analysis across different wavelengths. This mode is especially valuable for aligning the experimental setup and ensuring consistency in the illumination of all plastic samples under investigation. The flashlight operates with either three AAA batteries or an 18650 rechargeable battery, offering flexibility in long-term experiments.

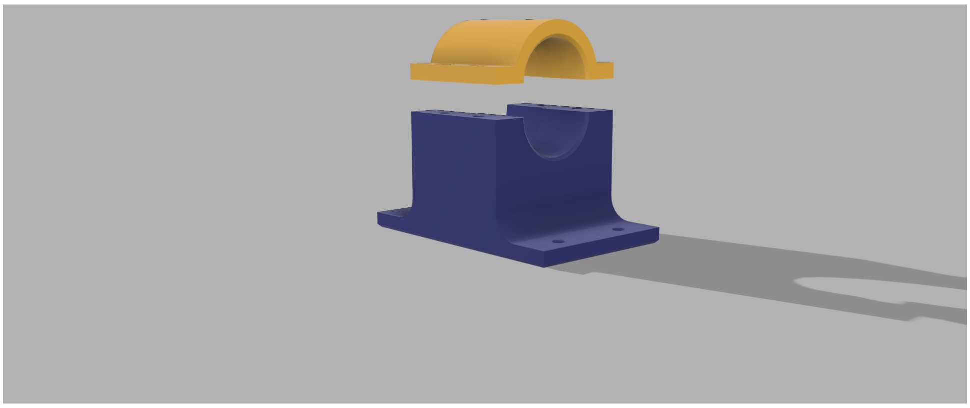

Figure 8.10: Light source holder 3D-Design

8.2 Materials used

Since the project focuses on differentiating materials used for 3D printing, the selected samples were chosen to be widely available and commonly used by FDM-3D printers.

8.2.1 Material: Polylactic Acid - PLA

PLA is arguably the most user-friendly 3D-printing Material. It is readily available and relatively cheap [32]. It does not require special precautions other than the proper printing nozzle and bed temperature.

8.2.2 Material: Acrylonitrile Butadiene Styrene - ABS

ABS is a popular 3D-printing material known for its strength and durability. It is more heat-resistant than PLA, making it ideal for functional parts. However, it requires a heated bed and proper ventilation due to the fumes it releases during printing. ABS is slightly more difficult to print than PLA but offers superior mechanical properties.

8.2.3 Material: Acrylonitrile Styrene Acrylate- ASA

ASA is a weather-resistant 3D-printing material. It offers UV stability and high durability, making it excellent for outdoor applications. It shares similar properties with ABS but is more resistant to environmental factors like sunlight and moisture. ASArequires a heated bed and controlled conditions to prevent warping, but it provides long-lasting, robust prints for demanding environments.

8.2.4 Material: Polyethylene Terephthalate Glycol - PETG

PETG combines the ease of PLA with the durability of ABS, making it a versatile material for 3D printing. It is strong, impact-resistant, and slightly flexible, suitable for functional parts. PETG prints without warping and doesn't release harmful fumes, but it requires a heated bed and careful tuning of print settings to avoid stringing.

Name	Melting Temperature /°C	Colour	Manufacturer	Product Name
PLA	190-230	black	Polymaker	PolyTerra PLA
PETG	230-240	black	Polymaker	PolyLite PETG
ABS	230-240	black	Verbatim	ABS
ASA	240-260	black	Azure Film	ASA Black

Table 8.3: Details of the materials used in this project

8.3 Measurement

Included in the PySpectrometer Project [30] was a software package that was designed to create measurements and usable data points from the Handheld Spectroscope. The package was designed for the use of a Raspberry Pi microcomputer in 2020 for a now-outdated platform. The project is not currently supported. The software side was designed to work with the hardware, providing real-time data acquisition, signal processing, and analysis through proprietary software. However, during the project, it was discovered that the original creator no longer supported the original software platform. This led to a critical challenge, as the software was essential for operating the spectrometer and processing the spectral data. The software component had to be substituted by an alternative solution to overcome this issue. A web-based platform was selected to replace the proprietary software, allowing data to be processed and analysed externally. This alternative solution, while functional, introduced some limitations, such as reduced real-time processing capability and less integration with the hardware control system. Despite these drawbacks, the measurement process could continue and the collected spectral data was processed successfully through the external platform, ensuring that the project could proceed as planned. Future work may involve developing a custom software solution that is fully compatible with the hardware and capable of addressing the limitations posed by the current web-based platform.

All samples were measured multiple times using different lights from the source to ensure complete data collection.

8.4 Raspberrry PI Setup

The setup for the Raspberry Pi was straightforward. First, the correct Operating System (OS) was chosen. Since there were no inherent specifications for the OS, a Linux distribution specifically designed for Raspberry Pi, Raspberry Pi OS was installed. After bootup, all necessary standard setup steps, such as network, location, etc., are completed.

8.4.1 Camera Sensor Setup

Since the Camera sensors that were used are compatible with the Raspberry Pi, the setup was also straightforward. There are two available choices. For 32-bit systems, the legacy camera has to be enabled in the raspi-config. For this project, a 64-bit OS was used; therefore, libcamera had to be utilised since the legacy camera was only supported on 32-bit systems.

8.4.2 libcamera

libcamera is an open-source camera stack. The goal of this project is to provide broad support to all camera types on different platforms, since embedded camera solutions usually rely on vendor-specific software [33].

9 Analysis and Interpretation of Results

Using the Web-based measuring alternative, the wave response of all samples was measured and recorded. The basis of all measurements was the comparison against a control measurement directly from the flashlight. This way, differences could not only be detected between the different samples but also from a steady baseline. The web-based application output is a graphical analysis of the waves reflected from the sample. The peaks and valleys of the graph can be recorded and matched to certain materials. The white light from the light source gives a broad spectrum, which allows a general classification of materials. The red, green, and blue light tests can create a more detailed representation of the wave profile of a material under test. For Example, in figure 9.1, the spectrum of an ABS measurement with white light can be seen. The significant peaks correspond with the red, green, and blue parts of white light. In measurements where a specific colour is used, the response usually shows only one peak. The position of the peaks, as well as the intensity, is recorded for every sample.

9.1 Different approach to NIR Spectroscopy

For this project, a method similar to Near-Infrared (NIR) spectroscopy was applied, but using only the visible light spectrum. While NIR spectroscopy operates in the range of approximately 780 nm to 2500 nm and is commonly used in industrial sorting systems, it often requires specialized and expensive hardware. To reduce cost and increase accessibility, this work uses a comparable approach but captures reflected light in the visible range (roughly 400 nm to 700 nm).

The underlying principle remains the same: different materials reflect and absorb specific wavelengths of light in unique patterns. By recording the intensity distribution across the visible spectrum

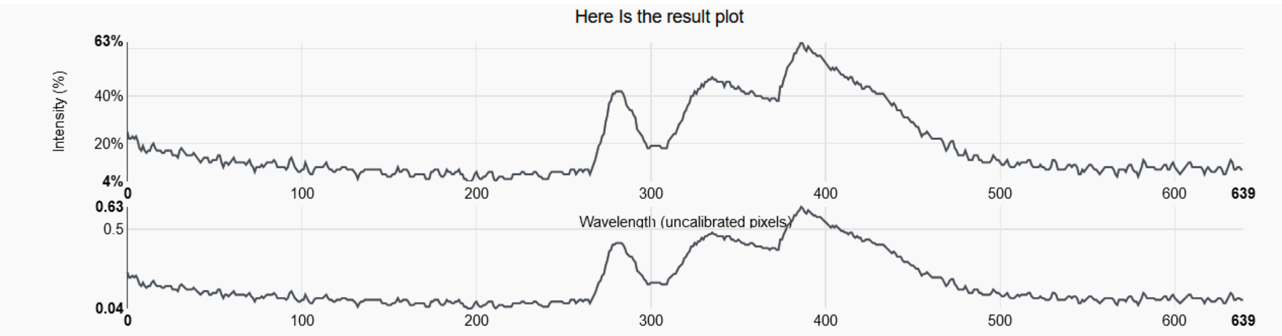

Figure 9.1: ABS-Measurement, White Light

and comparing it across samples, it is possible to identify certain materials—albeit with less precision than in the NIR range. While this approach lacks the molecular-level specificity of NIR or MIR systems, it offers a practical and low-cost solution for basic plastic differentiation.

This method was implemented using a standard RGB camera and a broad-spectrum light source. The data was then processed to extract relative intensity curves and evaluate whether material-specific signatures could still be observed in the visible band.

9.2 Mathematical Method for Spectroscopy Analysis

The data from the spectrometric analysis consists of a matrix of results. Usually, a table that represents an intensity for each wavelength of light. Each column represents a wavelength, and each line provides the data for a given sample/curve. This kind of dataset is suitable for visual representation but not for mathematical analysis. The calculation will be shown with example values.

9.2.1 Normalisation of Data

Wavelength (nm)	540	541	542	543	...	...	749	750
Intensity Sample1	27.5	30.6	33.9	37.7	...	...	199.9	198.4
Intensity Sample2	25.5	26.7	29.6	35.9	...	...	180.5	186.3
...	...	...	...	...	...	...	...	...

Table 9.1: Example values for Spectroscopy measurement

The raw example data is shown in table 9.1 [34].

The first step is to create a normalised matrix. To achieve this, the values get subtracted from the average value of this matrix. The mean value will be determined for every row of values regarding a specific wavelength. Subsequently, each value is subtracted from that mean value [34].

The resulting matrix can be seen in table 9.2.

Wavelength (nm)	540	541	542	543	...	...	749	750
Intensity Sample1	1.8	3.07	3.43	3.1	...	...	14.17	9.97
Intensity Sample2	-0.2	-0.83	-0.87	1.3	...	...	-5.23	-2.13
...	...	...	...	...	...	...	...	...

Table 9.2: Normalised matrix of exmple values

Now the data points indicate how far off the intensity of the sample is from the mean value, which is far more meaningful than absolute values. Another notable change is the occurrence of negative values for datapoints that fall below the mean value. If each element of the initial matrix is represented by q_{ij} [34].

Then this operation can be described by equation 9.1

$$X_{ij} = q_{ij} - \overline{q_i} \tag{9.1}$$

where X_{ij} is the normalised Value, q_{ij} is the original value and $\overline{q_i}$ is the mean value of the corresponding measurement.

9.2.2 Correlation Matrix (R)

After creating the normalised matrix, the correlation matrix has to be constructed. This matrix shows how the variables are correlated. This can be achieved by multiplying the normalised data matrix by itself as shown in equation 9.2.

$$R = X^T \cdot X \tag{9.2}$$

This results in a matrix where each element is given by the equation 9.3.

$$r_{jj'} = \sum_{i=1}^{n} x_{ij}x_{ij'} = \sum_{i=1}^{n} \frac{(q_{ij} - \overline{q}_j)(q_{ij'} - \overline{q}_{j'})}{\sigma_j \cdot \sigma_{j'}} \tag{9.3}$$

$r_{jj'}$ is a standardised covariance with a value between -1 and 1 in this context. It is important to note that this matrix is a Hermitian matrix, meaning it is symmetrical in the case of real variables [34]. Also notable is that the actual values of the wavelength are not mathematically relevant for this process.

9.2.3 Diagonilisation

The diagonalisation process results in 2 datasets: the eigenvalues and Eigenvectors of the variables. The eigenvectors constitute a new base or direction in which the data tends to vary. The Eigenvalues quantify how much weight each direction of the Eigenvector holds. The Eigenvalues are represented by matrix K in 9.4 [34].

$$K = \begin{bmatrix} \lambda_1 & 0 & \cdots & 0 \\ 0 & \lambda_2 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & \lambda_n \end{bmatrix} \tag{9.4}$$

Each λ_i in K represents the weight of the specific eigenvector through the relationship of the Eigenvalue divided by the sum of all eigenvalues $\lambda_i / \sum \lambda_i$. Once the base that maximises the variance is determined, 9.5 is derived [34].

$$S = V \cdot Q \tag{9.5}$$

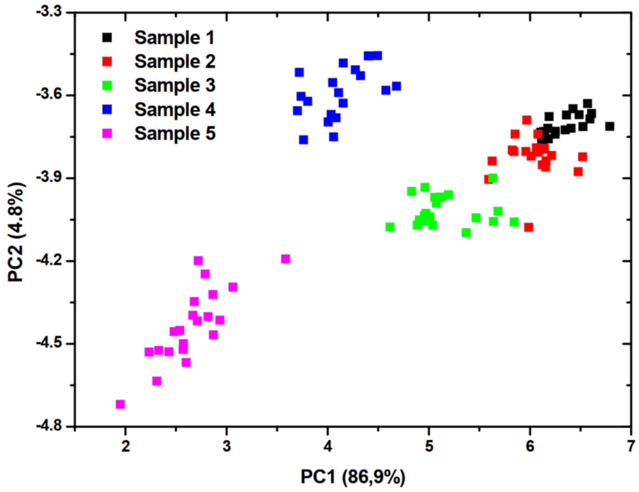

Figure 9.2: PC1 vs. PC2 of Sample Variance [34]

The transformation from matrix data S into the matrix Q by the base that maximises the variances is called the Karhunen-Loève transformation. The Elements in the matrix S are still correlated to a measure or spectrum demonstrated in table 9.3.

	PC1	PC2	PC3	PC4	...	...	PCN-1	PCN
Intensity Sample1	0.6	0.4	0.7	1.1	...	...	2.0	1.7
Intensity Sample2	0.8	1.2	1.4	2.2	...	...	1.7	0.6
...	...	...	...	...	...	...	...	...

Table 9.3: Available data with new base

Instead of analysing the data, which holds the intensity per wavelength, the data now indicates the variance of the values. This leads to a significant decrease in the datapoints that are analysed. Suppose a spectroscopy measurement includes 1.000 wavelengths, then 100. Data points have to be analysed. Through this mathematical operation, 90% of the data is captured in just two components of this new base. If the first two components of each sample are combined in a 2D graph, then it becomes clear how this method leads to a more straightforward identification solution. Instead of multiple lines on a curve, which requires multidimensional data processing, this analysis provides all measurements on a 2d-plot as seen in the figure 9.2.

This graph shows how densely the different samples are separated on the plot. This input data is a perfect starting point for computational analysis and even AI data processing.

9.3 Result of Measuremnts

While the goal was to apply the principle of NIR spectroscopy using only the visible light spectrum, the results unfortunately did not show useful information to be used. The system worked in the sense that spectral data was recorded and measured, but it did not lead to the desired result. As seen in

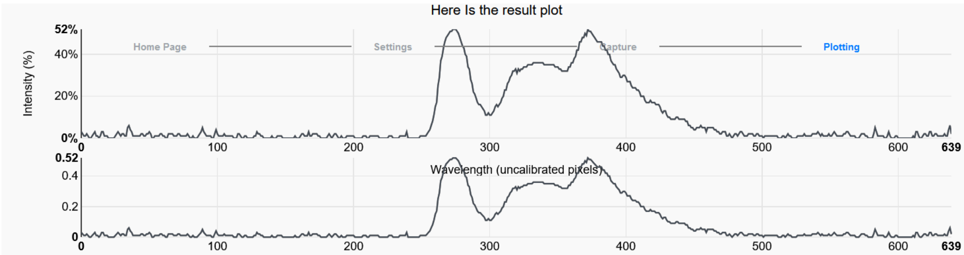

Figure 9.3: Measurement of ASA with white light

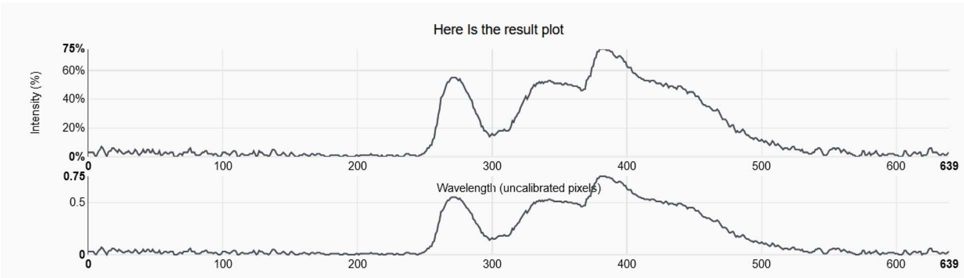

Figure 9.4: Measurement of PETG with white light

figures 9.3 and 9.4, the measurements do not create distinguishable "fingerprints". Therefore, no discrimination can be made based on this process.

There are multiple explanations why the results are not satisfactory. The materials (such as PLA, PETG, ABS, and ASA) that were used show very similar properties in the visible light range. Even if different pigments or colours where to be tested, the reflectance patterns show too little variation to build a clear distinction between materials. Without access to the more detailed molecular absorption features found in the NIR or MIR spectra, the visible light method lacks the resolution needed for reliable classification.

As a result, this approach was not suitable as a standalone method for plastic identification. However, the experiment confirmed that cost-effective setups based on visible light alone are not sufficient for material-level sorting, reinforcing the value of true spectroscopic systems operating in broader wavelength ranges.

9.4 Evaluation of NIR Spectroscopy for Plastic Discrimination

9.4.1 Cost

Industrial High-precision setups come with a significant initial financial investment. The quality of the system is highly dependent on the sensitivity of the sensors, the quality and purity of the light source and the precision of the optics setup. One of the most essential parts of the system is the processing unit, which, depending on the requirement, can be a significant cost factor. As seen in the experimental section, each component has low-cost substitutes. The drawback of these components is the inaccuracy each part introduces. These errors accumulate and can make such systems unusable.

The running cost is generally very low once the system is calibrated correctly. The maintenance consists of regular replacements once a fault occurs.

9.4.2 Accuracy and Efficiency

Industrial NIR spectroscopy is known for its high accuracy in identifying many different plastics, such as PE, PP, PET, PS, and others. This process is based on the principle of absorption and reflection of specific wavelengths of near-infrared light, which allows the user to capture a pattern unique to each polymer. When implemented in large-scale industrial conditions, it allows for quick, contactless, and real-time sorting with high reliability.

9.4.3 Small-Scale Reproducibility

The scalability of NIR spectroscopy to small or laboratory-scale systems is actually relatively feasible. Compact, handheld NIR spectrometers are available; some are even compatible with open-source software, making experimentation more accessible. Most of these spectrometers are meant for handheld applications, which adds the challenge of mounting a camera and appropriate optics to them. However, achieving reliable, reproducible results requires proper calibration, consistent lighting conditions, and control over sample presentation. Building and developing such a system from scratch requires a high level of expertise not only in electronics and software development, but also in optical technologies and measurements. Therefore, while NIR spectroscopy can be reproduced at more minor scales, it is not a plug-and-play solution and poses challenges for inexperienced users or low-resource settings.

9.4.4 Environmental Impact

NIRS spectroscopy is a clean, non-invasive technique that does not rely on chemical reagents or produce emissions during operation. It uses low-power light sources and has minimal energy consumption relative to mechanical or thermal methods. Furthermore, the technique reduces the need for manual sorting and can increase the throughput of recycling facilities, contributing indirectly to higher recycling efficiency. On the downside, the manufacture and eventual disposal of acNIR sensors, electronics, and optics involve materials with their environmental footprints, such as rare earth elements and speciality semiconductors. Nevertheless, regarding operational sustainability, NIR is considered to have a low environmental impact.

9.5 Lessons Learned

This project explored several established experimental approaches for plastic identification and sorting, with a strong focus on small-scale, low-cost implementation. One of the key learnings one can take away is that industrial methods such as NIR spectroscopy are extremely effective, their core principles cannot always be directly applied using simplified or cheaper components without a significant loss in accuracy. The attempt to replicate NIR spectroscopy using visible light highlighted the limitations of low-resolution data and the challenges in distinguishing between plastics with similar properties.

Another important aspect is the role of the experimental setup and controlling the environmental conditions. Even small factors such as lighting consistency and camera calibration can affect measurement quality. This shows just how important system stability and controlled conditions are, even more so for low-budget setups.

Lastly, it became clear that no single method alone can be efficiently used for plastic sorting. A combination of multiple techniques — spectroscopy with density-based separation — could provide better results than a single process on its own. The work also showed the importance of a system that can be adapted for different applications, allowing different methods to be tested or upgraded as needed. Overall, this thesis provides help to define what processes are able to be implemented considering the cost, space, and hardware restraints, and where compromises may affect the quality of the results.

10 Conclusion & Outlook

This thesis provided a basic explanation of the challenges of modern-day waste recycling. The fundamental waste sorting processes were identified and examined for various characteristics regarding small-scale, low-cost plastic sorting systems. Optical sorting, Density-based sorting and Near-Infrared Spectroscopy have been explored further and explained in more detail. These processes were not only examined and evaluated but also used to demonstrate different adjacent technologies like Machine Learning and how to choose the correct hardware for a specific application. For the experimental part of this thesis, a DIY NIR Spectroscope was constructed as a proof of concept. Based on a design that was developed for testing laser frequencies, this spectroscope demonstrated the steps for hardware and software design that are significant for such a delicate instrument. The data, which was inconclusive, demonstrates the level of complexity of these systems. By providing both a broad assessment and targeted experimental insights, this thesis establishes a foundation for future research. Subsequent studies may now focus on refining individual processes, improving automation, and adapting these techniques for broader industrial applications, thereby contributing to more sustainable practices in additive manufacturing and beyond.

10.1 Outlook

This section examines the possible innovations and directions that can be developed based on this thesis. The goal of this thesis was to provide a broad base for future academic and applied works.

10.1.1 Plastic recycling

As laid out at the beginning of this paper, the quest for an efficient way to recycle plastic started decades ago. Nevertheless, research still needs to be done to provide reliable and sustainable solutions for Earth's waste problem. Based on this thesis, small-scale plastic recycling operations, be it 3D printing or otherwise, can be developed and implemented for educational purposes as well as for actual use.

10.1.2 Technical Improvements

The focus of the experimental part of the thesis was to create a basic and low-cost solution, and it relied on specific components with no speciality in mind. Suppose one of the used components is substituted for a professional-grade tool. In that case, the difference in quality might show which of the used components has the most effect on a successful outcome. This way, the system could remain relatively low-cost if only one component has to be substituted for a more expensive solution. Another way this experimental setup could be improved is by developing custom software for measurements. This would increase the flexibility of the system and could be designed for a specific application.

10.1.3 Alternative Approches

Not only did this thesis prove different approaches to waste separation and examine their usefulness, but it also showed which approaches are not ideal and do not work within the given parameters. This opens the door to exploring alternative techniques and developing different systems based on this learning.

10.1.4 Narrowed Down Research

This thesis also gives a ground-level understanding of different waste separating techniques that can be further examined and developed more precisely. For instance, specific processes such as NIRS or density-based separation can be further optimised, adapted to different waste streams, or integrated into more sophisticated automated systems. The groundwork laid by this study thus provides a foundation for targeted investigations aiming to improve the efficiency, accuracy, and scalability of recycling technologies in laboratory or industrial environments.

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List of Abbreviations

AES Atomic Emission Spectroscopy

ABS Acrylonitrile Butadiene Styrene

ASA Acrylonitrile Styrene Acrylate

ASIC Aplication-Specific Integrated Curcuit

AI Artificial Intelligence

CPU Central Processing Unit

CCD Charged-Couple Device

DLP Digital Light Processing

EPR Extended Producer Responsibility

EMI Electromagnetic Interference

FDM Fused Deposition Modeling

GHGS Greenhouse Gases

GPU Graphic Processing Unit

HSI Hyperspectral Imaging

HDPE High Density Polyethylene

HMI Human Machine Interface

IR Infrared

IC Industrial Computer

LDPE Low Density Polyethylene

MDS Agnetic Density Seperation

MDP Markov Decision Process

ML Machine Learning

MLAS Machine Learning Assisted System

MRF Material Recovery Facility

MIR Mid Infrared

NMR Nuclear Magnetic Resonance

NMRS Nuclear Magnetic Resonance Spectroscopy

NVMe-SSD Non-Volatile Memory Express Solid State Drive

NIR Near Infrared

NIRS Near Infrared Spectroscopy

OS Operating System

PMT Photomultiplier Tube

PE Polyethylene

PETG Polyethylene Terephthalate Glycol

PET Polyethylene Terephthalate

PLA Polylactic Acid

PLC Programmable Logic Controler

PP Polypropylene

PS Polystyrene

PC Polycarbonate

PVC Polyvinyl Chloride

PCA Principal Component Analysis

RGB Red Green Blue

RIC Resin Identification Code

SATA Serial Advanced Technology Attachment

SLS Selective Laser Sintering

SLM Selective Laser Melting

SLA Stereolithography

SCADA Supervisory Control and Data Acquisition

TPU Tensor Processing Unit

UV Ultraviolet

WTE Waste to Energy

XAS X-Ray Absorbtion Spectroscopy

XRF X-Ray Flouresence

XRD X-Ray Diffraction